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A Structured Reasoning Space for Design of Complex, Socio-Technical Systems

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Air Force Research Laboratory
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14. ABSTRACT

This research project was undertaken to develop a concept for representing the products of a Cognitive Work Analysis (CWA) in a comprehensive, integrated fashion that would better support the application of Cognitive Systems Engineering practice within the traditional Systems Engineering process. CWA takes a more structured approach to representation than is common within Cognitive Systems Engineering. It is a multi-phase analytic process that develops representations for functional structure, tasks, strategies, collaboration and individual cognitive performance. Currently, its representations are difficult to interpret and do not serve well as design artifacts. The specific issue addressed is representation of the work domain and the activity within it in a form such that all involved in a developmental project can understand the domain well enough to design solutions for the cognitive challenges faced by the human operators of the envisioned system. The concept of an information environment to support system design is introduced, and leads into a vision for an information structure—a "reasoning space." A reasoning space supports the natural information-seeking strategies used in human problem resolution by encouraging an opportunistic trajectory through a comprehensive and global information space. The reasoning space described here lays out information at different levels of abstraction and degrees of decomposition in a structure that reveals the significance of interdependencies between specific details while taking account of global constraints. It uses a pictorially rich format that facilitates an intuitive grasp of subtle and complex concepts. The purpose of this reasoning space is to help a design team identify forms of functional reorganization or work support that may assist workflow in a complex, socio-technical system. Within our current socio-technical work environments in which operational personnel discard many new support systems because they are too cumbersome or too poorly conceptualized, use of a reasoning space in this manner could constitute a huge advance. A case narrative based on Time Sensitive Targeting in an Air Operations Center is developed to illustrate the use of the reasoning space in the development of technological innovation.

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PREFACE

This research was conducted under contract number FA8650-04-C-6538 with the Cognitive Systems Branch, Warfighter Interface Division, Human Effectiveness Directorate of the Air Force Research Laboratory (AFRL/HECS), Wright-Patterson Air Force Base, Ohio 45433-7022, for the period September 2004 to July 2006. General Dynamics – Advanced Information Systems, 5200 Springfield Pike, Dayton, Ohio 45431 was the contractor. Dr. Gavan Lintern was the Principal Investigator. Dr. Edward A. Martin (AFRL/HECS) was the Program Manager. This effort supported Work Unit 7184D121, "Representing Cognitive Demands of New Systems."

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INTRODUCTION

Structure of this Report

The research reported here was undertaken to develop a concept for representing the products of a Cognitive Work Analysis in a comprehensive, integrated fashion that would better support the application of Cognitive Systems Engineering practice within the systems acquisition process. This report first provides some background regarding the problem area and the scope and objectives of the research. It then introduces the subject of an information environment to support system design, leading up to a vision for an information structure—a "reasoning space." This report then illustrates how a human-systems designer or analyst might use the reasoning space to understand a work domain using the context of a Time Sensitive Targeting cell in an Air Operations Center.

Appendices A and B provide some tutorial material regarding the Work Domain Analysis phase of a Cognitive Work Analysis. Representational issues and forms are the topic of Appendix C. The relationship of Work Domain Analysis to traditional systems engineering analyses is the topic of Appendix D. Appendices E through J document some of the exchanges Dr. Lintern had with Subject Matter Experts while conducting the research and exploring ideas and approaches for this project, and Appendix K concludes with some thoughts stimulated by those exchanges.

Background

Cognitive Systems Engineering is an analysis and design discipline for Human-System Integration within socio-technical systems. Analytic methods focus on the complexities of work by identifying why the work is cognitively difficult, the types and levels of expertise required, the functional or informational structure of the work domain, the tasks or processes employed, the means by which workers develop situation awareness, and the means by which workers coordinate and communicate.

The specific goal of Cognitive Systems Engineering is to represent the work challenges in such a manner as to inform human-centered design. Analyses typically lead to forms of dialog or representation that are intended to support the design of process and technology involved in cognitive work. Knowledge representation is, however, a troubling problem. We have many techniques for collecting work-related information but representation of that information is typically guided by preference or intuition rather than by a systematic understanding of representational concepts.

Cognitive Work Analysis takes a more structured approach to representation than is common within Cognitive Systems Engineering. It is a multi-phase analytic system that develops representations for functional structure, tasks, strategies, collaboration and individual cognitive performance (Figure 1). Although comprehensive, its representations are nevertheless difficult to interpret and do not serve well as design artifacts, presumably because they are predominantly symbolic and do not provide evocative distinctions between functions and processes that should be distinguished. A representation is, in some sense, intended to offer a picture, but for any reasonably complex system, its topographical homogeneity defies exploration in the pursuit of understanding as, for example, is possible with a representation of an actual scene or even with a well-designed map of a geographical area. Thus, there is a general issue here; how can Cognitive Systems Engineers represent the work domain and activity within it so that all involved in a developmental project understand the domain well enough to design solutions for the cognitive challenges faced by the human participants in the system.

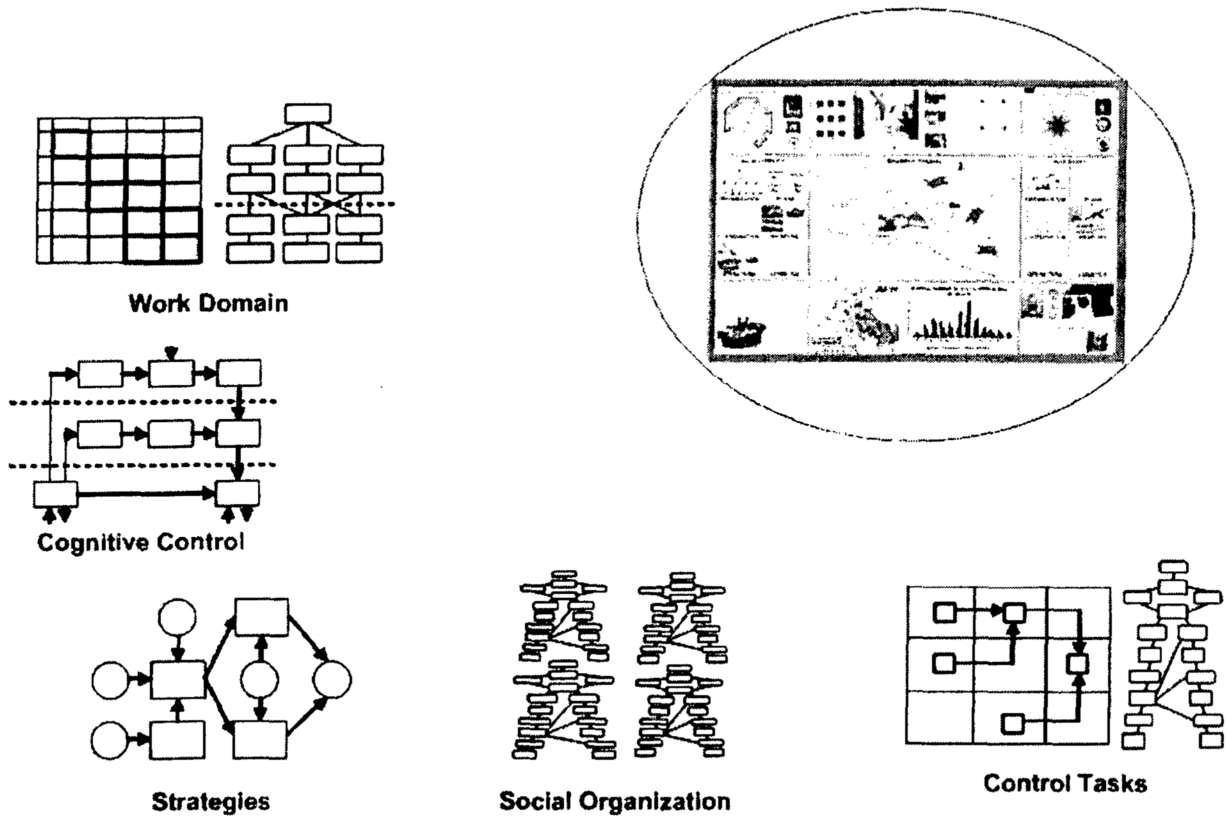

Figure 1: Cognitive Work Analysis is a multi-phase analytic framework that results in design specifications for functional structure, tasks, strategies, collaboration and individual cognitive performance

A Systems View

Cognitive Systems Engineers typically focus on bounded design problems (e.g., how to design an interface, how to build a decision support system or how to design a team structure). These types of interventions are typically guided by analysis of a particular problem area rather than the whole system. Work may be facilitated locally but there may be no value added to total work output and there is even the possibility that a local intervention will negatively impact some other aspect of the system. Cognitive Work Analysis was developed for the more extensive problem of human-centered design for a complex, socio-technical system. Practitioners of Cognitive Work Analysis typically gravitate towards trying to understand:

- The functional structure of the system, and
- How issues are resolved and work tasks are executed within that functional structure.

In particular, they seek to understand the functional system organization so that they do not develop solutions to local problems that impair global effectiveness.

In a pioneering effort, Naikar, Pearce, Drumm, and Sanderson (2003) demonstrated how Cognitive Work Analysis could be use to develop and represent specifications for a *first-of-a-kind* system. The project reported here builds upon that and other work, focusing on the following issues:

- The distinction between structure and process,
- The role of representation as a design artifact, and
- The integration of different representations as a coherent design artifact.

Project Requirements

The requirements for the project were to develop and demonstrate representational forms for cognitive processes and work structures as follows:

- Develop a representational form for work process, consistent with the theory of Cognitive Work Analysis, that can be linked closely to the structural representation derived from Work Domain Analysis
- Demonstrate how this representational form can be used within a Command and Control domain
- Develop visualization examples, derived from the combination of structure and process representations, that depict the diverse cognitively-relevant facets of a complex socio-technical system
- Outline specifications for a computerized tool that will allow these representations to be viewed in combinations and configurations that dynamically illustrate the progress of a work narrative by sequential highlighting of the elements within any or all of the representations.

The goal of this project is to develop a representational form that can support exploration of cognitive demands within the acquisition process for a *first-of-a-kind* system.

At the time of writing the proposal for this work it had seemed possible that representations used in Systems Engineering might offer a guide to development of more intuitive representations for Cognitive Systems Engineering. Within this project, and within other projects, I have sought the views of the Systems and Design Engineers and have reviewed Systems Engineering textbooks and reports. The Department of Defense Architectural Framework (DoD Architecture Framework Working Group, 2004) is impressive in the number and diversity of representations it uses for systems design. Nevertheless, I have concluded from my review of representations used within Systems Engineering that they suffer from same limitation of topographical homogeneity as do the representational artifacts commonly used within Cognitive Systems Engineering. They are equally schematic and are unlikely to be any more effective as artifacts—at least for the design of cognitive systems. Thus, it seemed necessary in this project to make a serious attempt to advance the state-of-the-art for representation as a system design artifact.

AN INFORMATION ENVIRONMENT FOR SYSTEM DESIGN

Information Sources for System Design

The general problem addressed here is that of understanding a complex, socio-technical system sufficiently to redesign its human-system interactions. The motivation for this project was derived partially from the inadequacy of current information sources for system design. Many practitioners in Cognitive Systems Engineering and related disciplines rely on interviews and discussions with subject matter experts and on-site observation to generate insights. However, subject matter experts can be parochial and may resist discussions of the comprehensive view that a designer or developer needs. Observation of the work can be insightful but some systems are so complex that it is difficult to get through the confusion period to start assimilating meaningful insights, and then the development of a comprehensive view can take a considerable time.

Within Cognitive Work Analysis, domain documents are used as one important source of cognitive knowledge. Problematically, military documents related to operational domains typically run into hundreds of pages. Furthermore, the structure and the abstract nature of the information content for similar topics is inconsistent between chapters; there is repetition of detail between chapters, and discussions of critical system dimensions found in some chapters are often omitted in others. A more structured, more consistent and more comprehensive presentation would be of considerable assistance to designers of systems as they struggle to understand the work domain.

An Information Environment for Knowledge-Based Reasoning

The motivation for development of an information environment to satisfy the requirement for a more structured, more consistent and more comprehensive presentation is derived from a concern about how we understand and reason through a complex issue with many interdependent dimensions. Typically, the dialectic among those who stand outside a knowledge domain revolves first around one issue and then another, often without clarifying the relationships between the two and without consideration of other critical issues. The dialectic can quickly degenerate into an agenda-driven discussion that subverts any attempt to reason about the workspace. In contrast, those who work within this type of knowledge domain do not typically develop an appreciation beyond their own sphere, and may converge on strategies that are locally optimum without full appreciation of the global constraints. They may fall into comfortable patterns and may fail (and even be reluctant) to explore options, some of which could be more effective.

The conceptual idea behind the design artifact, or *reasoning space*, developed in this project is that a cognitively compatible information environment will:

- Support an exploratory trajectory through the resources and functions of the work domain at various levels of abstraction and decomposition, and
- Reveal how functions at one level of abstraction are realized by use of resources or functions at the level below.

It will thereby encourage systematic and comprehensive exploration of a problem.

The design of the information environment developed here was guided by the foundational belief that effective reasoning relies on access to comprehensive information about functional structure and about interdependencies within that structure. Comprehensive information is not, however, sufficient. That information must be organized and presented so that those reasoning through it can converge quickly on the elements of information that are central to the current discourse and can then link those elements to construct an information constellation in which relationships between nodes reveal cause, influence, dependency and effect.

The structure of this reasoning space is based on Rasmussen's theory of problem solving and troubleshooting (Rasmussen, 1986). The general solution prototyped here for this challenge is a pictorially-rich reasoning space structured in a manner that shows resources and functions and how they can be used to accomplish productive work within the constraining values and priorities. The structure conforms to Rasmussen's Abstraction-Decomposition space; a representation that reveals interdependencies between information at different levels of abstraction and decomposition in a representational form that supports intuitive and seamless navigation. It does so in a manner that permits those reasoning about local issues within the space to explore different functional configurations that remain consistent with global coherence. As discussed by Rasmussen, Pejtersen and Goodstein (1994), normal human problem-solving trajectories map naturally to the Abstraction-Decomposition space. In that sense, the Abstraction-Decomposition space is a cognitively natural representation for reasoning about complex systems.

This information environment will support Knowledge-Based Reasoning rather than Skill- or Rule-Based Reasoning in the selected knowledge domain—although it could serve as a learning environment to help users develop or retune their Skill- and Rule-Based Reasoning strategies. It will be possible, for example, to prepare the information environment so that it supports the Knowledge-Based Reasoning used by novices as they develop their Skill- or Rule-Based expertise. The conceptual nature of this information environment is general. It can potentially be populated with information relevant to any knowledge domain.

Issues of Human-Systems Integration in System Design

Much of Human Factors deals with the design of workstations for single operators but Cognitive Systems Engineering is (or at least should be) concerned with design relating to issues of cognitive demand as they emerge throughout the design cycle. For complex, distributed work systems, decisions made during the concept refinement and technology development phases impact the effectiveness of the system. Issues related to cognitive demands move from abstract to concrete and become more extensive and detailed as system development progresses through the concept and technical phases (Figure 2).

It is common for Human Factors Engineers and Cognitive Systems Engineers to express concern about the failure of Acquisition Managers to involve them in resolution of human-systems issues right from the start of concept refinement. While the implication of this complaint is that Acquisition Managers do not understand the significance of our potential contribution, I rather believe that we have not had the tools that would permit us to be effective in the concept refinement phase. One goal of this project is to develop a tool that can correct that deficiency.

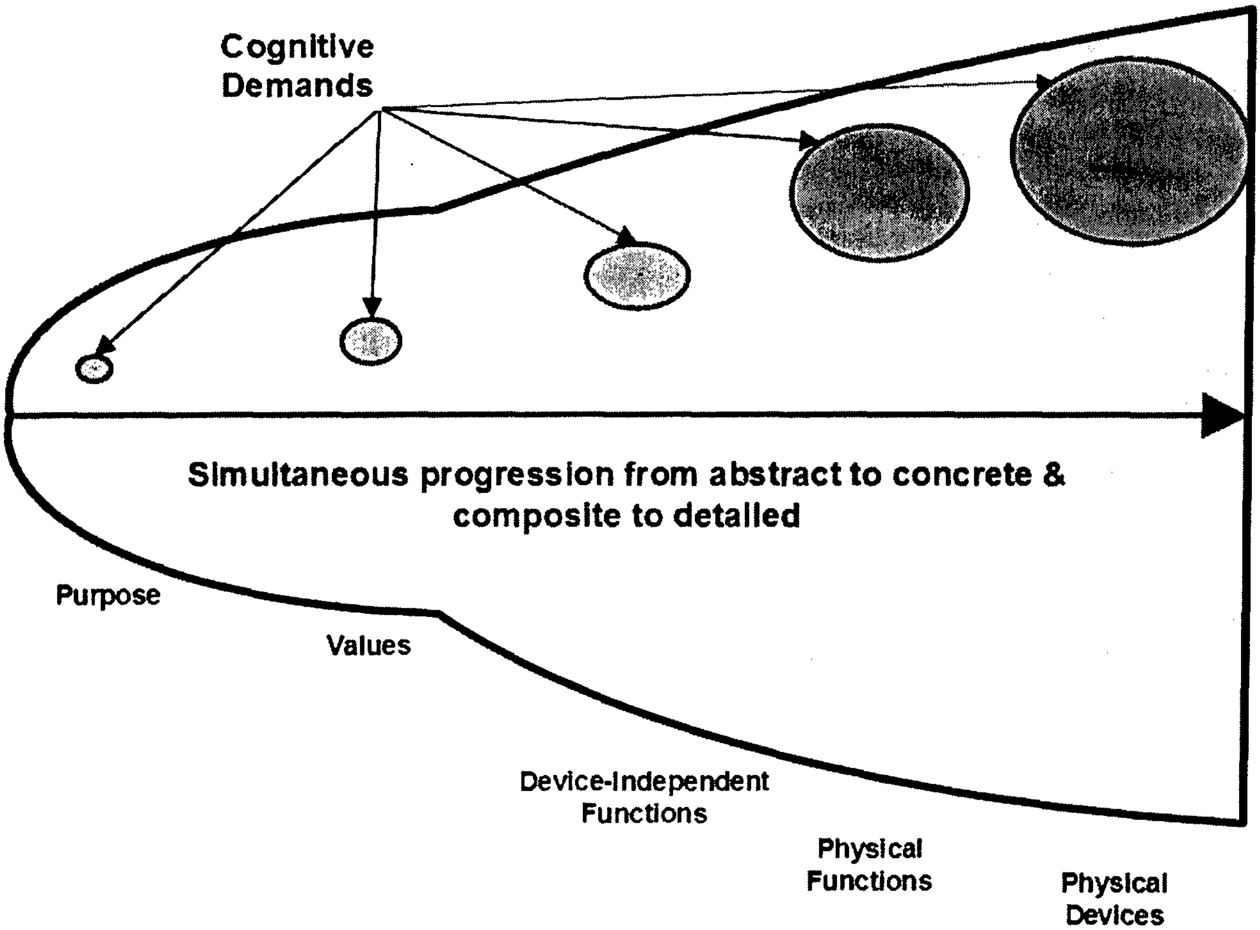

Figure 2: Issues related to cognitive demand for collaborative, distributed work become increasingly concrete and detailed as systems development progresses through concept refinement and technology development

The representational products of Cognitive Work Analysis constitute a structured, consistent and comprehensive description of an operational domain from a systems perspective, one that bears on human-systems issues relevant to the concept refinement phase of systems development. It is generally intended that these products be developed by a small team of analysts and then be used by other members of the design team. However, the resulting representations are typically too schematic for anyone other than those directly involved with the analysis to understand. Nor do they encourage engagement by subject matter experts who might be able to enrich the results of analysis if they could understand the analytic products. Similarly, those who fabricate systems (e.g., software engineers) typically ignore the analytic products of Cognitive Systems Engineering because they do not find them informative. The purpose of the information prototype developed here is to demonstrate how it is possible to remain consistent with the principles of Cognitive Work Analysis, and yet develop richer and more meaningful representations that, despite their richness, remained succinct enough to highlight the critical features and relationships.

Thus, the principal objective of this project is to demonstrate a style of integrated representation for work structure and the cognitive processes that operate within it that is more readily interpretable by those who are not Cognitive Systems Engineers, who have not participated in the analysis, and who have little knowledge of the work domain.

THE FORM AND STRUCTURE OF A REASONING SPACE

Information Structure: The Vision

The general concept is a visualization of functional structure in the form of a multilevel view that extends the abstraction-decomposition depiction into three dimensions so that each level is represented spatially, with objects in it represented evocatively by graphics, icons, pictures or even video or audio clips. The functional nodes will be connected via means-ends relations *between* adjacent levels of abstraction and through decomposition links *within* abstraction levels. Because Abstraction-Decomposition spaces of large systems can be complex, possibly containing several hundred nodes (Naikar & Sanderson, 2001), some of the features implemented in the Work Domain Analysis Workbench developed by Sanderson, Skilton, Cameron and Cao (1998-2000) may be useful. This Workbench permits selection or highlighting of various parts of the Abstraction-Decomposition space, for example a decomposition cluster or families of functions as connected through means-end links. These selection capabilities are particularly useful for enabling visualization of various functionally interdependent regions of the space.

Information sets will be tuned specifically for human-systems design. In effect, any customized tuning for a specific purpose will omit a considerable amount of information about a work domain. If the selection is well judged, the excluded information will not diminish the practical value of the information environment for the targeted purpose. Note that the emphasis here is on work rather than tasks. A constrained and specific constellation of information is typically needed for a particular task, but the set of tasks that might be undertaken in that workspace (i.e., the work) will require a much broader set of information. A comprehensive information analysis, such as provided by Cognitive Work Analysis, is essential to uncover that broader information set.

While implementation of a simulation engine is beyond the scope of the current project, a simulation engine will lie behind the information structure in its final form. That simulation engine will be used to execute fragments of prototypical tasks (some of them edge cases). A designer will be able to monitor scenarios as they unfold at a selected speed, and will be able to stop and reverse the simulation at will to capture moments that can then be composed into a time-line depiction (a four-dimensional visualization). It will be possible to execute the simulation within any of the abstraction levels, which will be linked through the means-ends relations so that the designer can track the task evolution across levels. Decompositions will also be linked so that the designer can track the task evolution within levels. At this time, it is thought that an extension of the Brahms simulation environment (Clancey, Sachs, Sierhuis, & van Hoof, 1998) can be adapted to this role.

The information structure has been developed in storyboard form in this report to show how a user can transition smoothly between representational layers to explore a problem. The information structure is as graphical and iconic as project resources and my own creativity have allowed, but conversion of many different types of concepts to iconic or graphical form poses significant conceptual and creative challenges. Inevitably, at least some of the content is described with text.

The Demonstration Concept for the Reasoning Space

The following sections of this report demonstrate a coherent and economical information space for a constrained knowledge domain. The concept of a reasoning space as developed in this report is generic in the sense that the style can be customized for any domain of complex cognitive work, and for any stakeholder or worker who participates within that domain. However the viability of the concept needs to be demonstrated with an illustrative example for a specific knowledge domain and stakeholder. The knowledge domain selected for illustration is Time Sensitive Targeting. While it might be useful to develop a knowledge domain for a broader problem space, it is more important at this stage to develop a concrete and coherent illustration. That, specifically, was the goal of this project. With an illustration in place, other researchers who grasp the concept are likely to have creative ideas to boost the technology.

To that end, the reasoning space developed here has been configured to support cognitive-systems analysts and designers who want to know about Time Sensitive Targeting in order to analyze or redesign its support tools or processes. With some adaptation of content, this reasoning space would be useful for others, such as design engineers, senior air operations command staff, or novice Time Sensitive Targeting operators.

In tuning the information structure of the reasoning-space for a specific stakeholder, the objective is to provide all essential but no superfluous information. In almost all cases, information systems are not only poorly organized but also have considerable information that is irrelevant to the stakeholder. Designers of information systems often take the attitude that they do not know what information stakeholders need and so they provide everything they possibly can. Designers who develop information systems of that type relegate their responsibility for identifying the critical information set to the stakeholder who uses it. In addition, information systems are often configured to satisfy the needs of many different types of stakeholders, which inevitably leads to much information that is irrelevant to specific stakeholders. There is no reason in this day of reconfigurable electronic documents that information systems cannot access a global information repository, but be customized for a variety of specific users.

I chose to tune the reasoning space for cognitive-systems analysts and designers primarily because:

- I, as the cognitive engineer working on this project, am a legitimate stakeholder and thus can tune it effectively (to tune it to another type of stakeholder or subject matter expert would have required intensive and extensive discussion with someone from that stakeholder or subject matter area, which was beyond the resources available for this project).
- The technical monitor for this project is also a legitimate stakeholder, and will be able to evaluate the product from that perspective, as will many of his colleagues.

It is content rather than structure makes this reasoning space specific to one type of domain and stakeholder. Retuning of the content will make it suitable for a different type of stakeholder.

THE AIR OPERATIONS CENTER: A BENCHMARK PROBLEM

In today's information intensive environment, the Air Operations Center can be viewed as a benchmark problem for design of a complex, socio-technical system. It has multiple agents, both people and information systems, with considerable need for coordination. Because the system has evolved over decades, with technological capabilities added in a fragmented and piecemeal fashion, the organizational structure and the communication and information support is not well integrated. Several different means of communication are available (chat, datalink, secure and non-secure voice) but it is not clear that these technological resources are ideal for the work they support. There is some movement of personnel around the floor of the Air Operations Center for face-to-face discussion and some collaborations are sustained by individuals pointing things out to each other on work station screens, but the configuration of the workspaces does not necessarily support those sorts of interaction. Large common screens for information display are available, but there does not appear to be any coherent understanding of how they might usefully support the work. Many disparate information systems are used to find information and post plans or decisions, but these too are not well integrated.

The modern Air Operations Center has evolved into a system with 1000 plus staff and many stove-piped information systems. Overstaffing can result in confusion and inefficiency. There is considerable need and considerable opportunity for redesign based on the fundamental constraints of the work, but there does not appear to be a coherent concept about how to proceed.

The Air Operations Center; Design Goals

The primary design challenge for a large, complex information system such as an Air Operations Center is the development of an efficient and effective system that fully integrates the various functional components of distributed, network-centric processes. While much of the solution lies in development and integration of technological capability, there are many Cognitive Engineering issues that must be resolved to establish effective system performance. Furthermore, in contrast to the common approach of developing technological solutions before addressing human-system integration issues, a redesign problem of this magnitude (and more generally, any explicit system redesign aimed at enterprise transformation) demands resolution of cognitive issues related to system purpose and high-level structure during concept refinement (Figure 2). Satisfactory resolution of those issues will ensure an appropriate functional layout and lead to an optimum staffing footprint in which warfighters with appropriate skills and appropriate training are assigned to fill each of the essential positions in the Air Operations Center.

Once the functional layout is determined and staffing assignments are established, critical cognitive process issues become evident; those such as how to support essential communications, how to support critical decisions, how to help warfighters build and maintain situational awareness of the common operating picture, how to avoid process bottlenecks and performance breakdowns caused by high workload, and how to enhance war-fighter performance with automation and decision aiding.

In an organization such as an Air Operations Center, resolution of these cognitive issues starts with the nature of the work. Analyses of functional structure and communication patterns are used to identify an optimum physical layout designed to facilitate collaboration and mission accomplishment. Appropriate functional allocation will ensure that the optimum staffing level is assigned to each work unit. The design goal is a staffing level and organization in which work packages are configured to ensure acceptable workload levels and economical communication overhead. The aim is a functional organization of collaborating agents (both human and automated) with the essential communication links and appropriate interfaces and decision support tools. Along with the staffing and workload distribution come training recommendations to ensure that the individuals allocated to each position have appropriate skills and expertise. A comprehensive and well-structured reasoning space has a large role to play in resolution of these sorts of design challenges.

The Use of the Reasoning Space

Elsewhere I have argued that modern design of complex socio-technical systems by large and diverse teams suffers considerably because we do not have a shareable design artifact that a design team can explore collaboratively to understand the nature of the work, the challenges to design, and potential design solutions (Lintern, 2006). The reasoning space described here is intended to serve as such a design artifact for one portion of the Air Operations Center, the Time Sensitive Targeting cell. Given sufficient resources, this reasoning space could be extended to cover the entire Air Operations Center.

There are two fundamental strategies by which a systems designer might become familiar with the complexities of a large-scale socio-technical system:

- Explore the space to examine the available resources and constraints, and how those resources and constraints can be accommodated to mission demands, and
- Work through scenarios to develop skill in use of the resources and to explore various ways of satisfying mission demands.

Typically, those who wish to design technological systems to be fitted into an Air Operations Center do not do much of either.

As a Cognitive Engineer, I have sought to execute the first strategy by reviewing and summarizing technical and operational documents. This can be both a time-consuming and frustrating process because many documents are verbose, disorganized and inconsistent. In addition, it is difficult for one person to create a summary document that can then be used by others on the design team to assimilate the essential understandings. I have sought to execute the second strategy by working through imagined scenarios as I examine the representations produced from a cognitive analysis I had undertaken on the relevant domain. While I have found that this procedure can work for me as an individual, the representations I develop in that way do not appear useful to others. My claim is that a graphical reasoning space, by revealing the functional properties of the domain and explicating the interdependencies between levels of abstraction and the relationships between degrees of decomposition in an evocative, pictorial form, provides a much better means of summarizing that knowledge so that others can readily assimilate it either by reviewing the functional properties or by mentally tracing scenarios through it.

Those who use the reasoning space to develop a deeper understanding of the domain would examine each node of the Abstraction-Decomposition space and trace through its links to other nodes, moving through levels of either decomposition or abstraction and then follow up by working through scenarios. In what follows, I storyboard both approaches to demonstrate the process of developing a deeper understanding of Time Sensitive Targeting. For purpose of illustration, I have developed a fictitious but generic scenario and have then worked through a storyboard narrative to demonstrate how the reasoning space might be explored by a human-systems designer who uses the reasoning space to become familiar with the work domain as a first step in designing human support systems for it.[1]

THE REASONING SPACE IN USE

Targeting Scenario

The notional scenario assumes a military action by US and allied forces in a country identified as Kartania. A forward base has been set up for the US Air Force in a neighboring country, Baranistan, and a US carrier task force is operating off the coast of Kartania (Figure 3). Certain routine operations are under way. An Unmanned Aerial Vehicle conducts surveillance from a regularly scheduled east-west route along the northern border of Kartania. Two air refueling patterns, one in central Kartania and one off the south coast of Kartania, are maintained by KC-10 aircraft.

During the early morning hours, human intelligence sources have notified their agency that the senior leadership of a significant insurgent operation is to gather during midmorning at an identified location. The human intelligence sources indicate that the meeting will commence at 10 a.m. and finish before noon.

A contingency air attack plan is in place to respond to this type of situation. The goal is a precision strike that will terminate all members of the top-level leadership group.

The Time Sensitive Targeting cell has been tasked to plan an air strike on the buildings in which the meeting will take place, to occur after all the key insurgent leaders have arrived. The Time Sensitive Targeting cell is to identify the strike aircraft and the ordnance to be used. They must also schedule fighter air cover as a contingency against enemy fighter support and Electronic Warfare air platforms to defend against enemy missile defenses. Air refueling will be scheduled as necessary.

The insurgent meeting is to be held in one of a cluster of three buildings. The specific building to be used for the meeting cannot be identified in advance. Although surveillance of the meeting site is to be maintained so that the arrival of the insurgency leaders can be monitored in real-time, the buildings are connected so that we cannot be sure the meeting will be conducted in the building the insurgents enter. Thus, the air strike is to destroy all three buildings.

The attack is complicated by the fact that this area is defended by a surface-to-air missile battery and the target is located in the middle of four sensitive structures, a house of worship to the southeast, a shrine to the west, a hospital to the northeast and a market to the north that will be

[1] Notional data are used to support the storyboard narrative, including aircraft range capabilities, fragmentation footprints, missile acquisition and intercept capabilities, radar capabilities, and jamming capabilities.

filled with noncombatants at the time of the strike (Figure 4). The strike plan must ensure that there is nothing more than superficial collateral damage and must also ensure the safety of all the US strike and support assets.

A contingency search and rescue plan is to be developed in case any air crewmembers have to eject from their aircraft.

Representation of Resources and Constraints

The implication of Rasmussen's theory of problem solving (Rasmussen, 1986) is that problem solvers navigate opportunistically through an Abstraction-Decomposition space. They inspect resources and functional capabilities to develop a strategy that brings functional capabilities into line with the purpose and values that act as constraints on action. There is no optimum starting point in the Abstraction-Decomposition space. The prime requirement is that the trajectory through the space visits the functional nodes that help the problem solver understand the situation and develop a plan that will satisfy the work demands. Targeting should conform to this pattern of behavior since planning is an exercise in developing a solution to a problem.

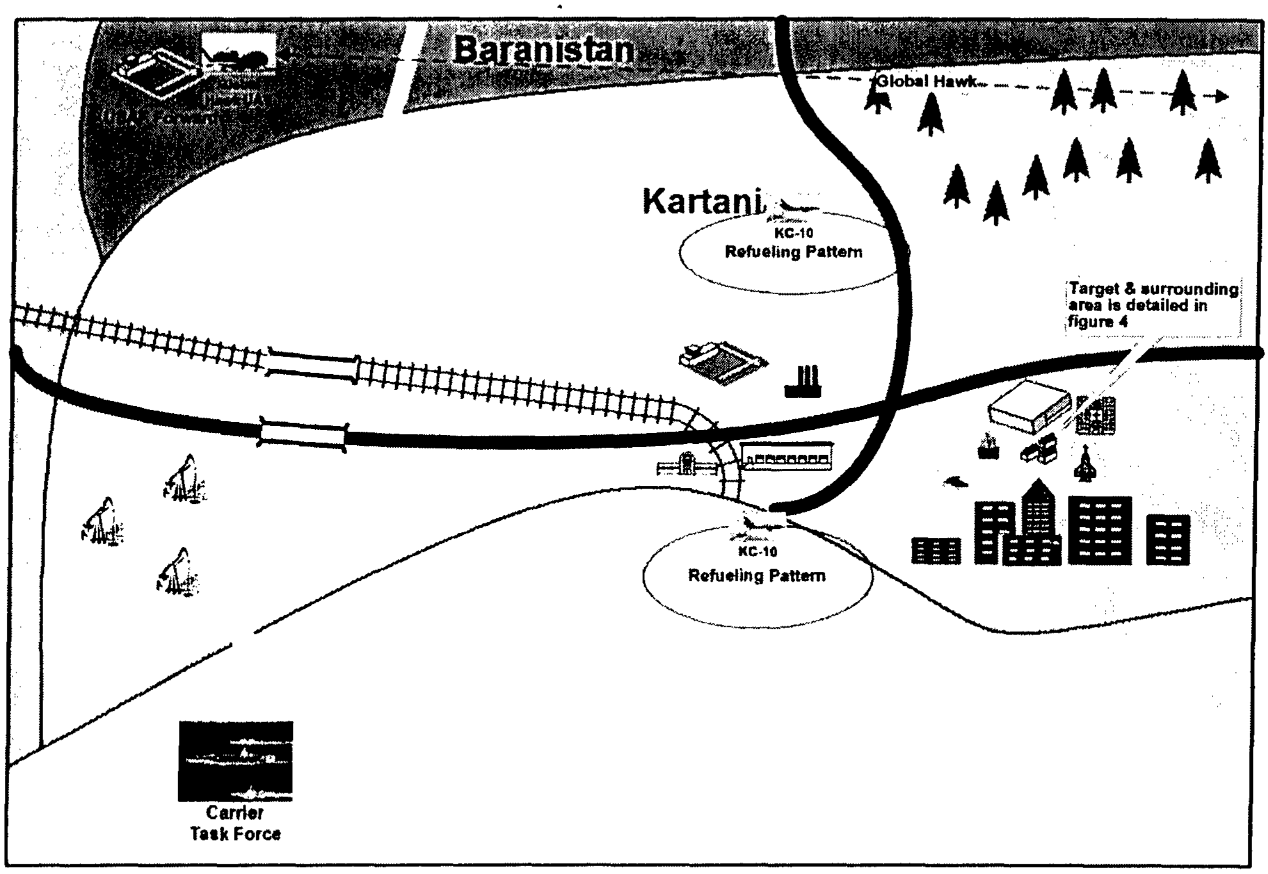

Figure 3: Area of operations for the notional targeting scenario

The narrative of the following paragraphs is fictional, created for the purposes of illustration. It is a description of a trajectory a human-systems designer might follow in seeking to become informed about the nature of the work of Time Sensitive Targeting prior to embarking on design of a support tool for this work domain. In practice, that human-systems designer would preferably confirm his or her newfound understanding by subsequently working though the space with a subject matter expert, and then might engage with others on the design team to again work through the reasoning space to help them generate a useful level of understanding about the work domain. In particular, the reasoning space is intended to be an exploratory and collaborative environment in which colleagues can work through problems and develop ideas in a manner that is not possible with a normal document or even with a graphically rich presentation.

In addition, readers should recall that this reasoning space has been customized specifically for the use of a human-systems designer rather than Air Operations staff. It should be remembered, however, that the concept of a reasoning space is intended to be generic. Thus, this Time Sensitive Targeting reasoning space could be customized for those who are to work as Air Operations staff but are, as yet, novices in this work domain, or it could even be customized for experts in this work domain who wish to explore new ways of doing things or strategies for dealing with difficult challenges.

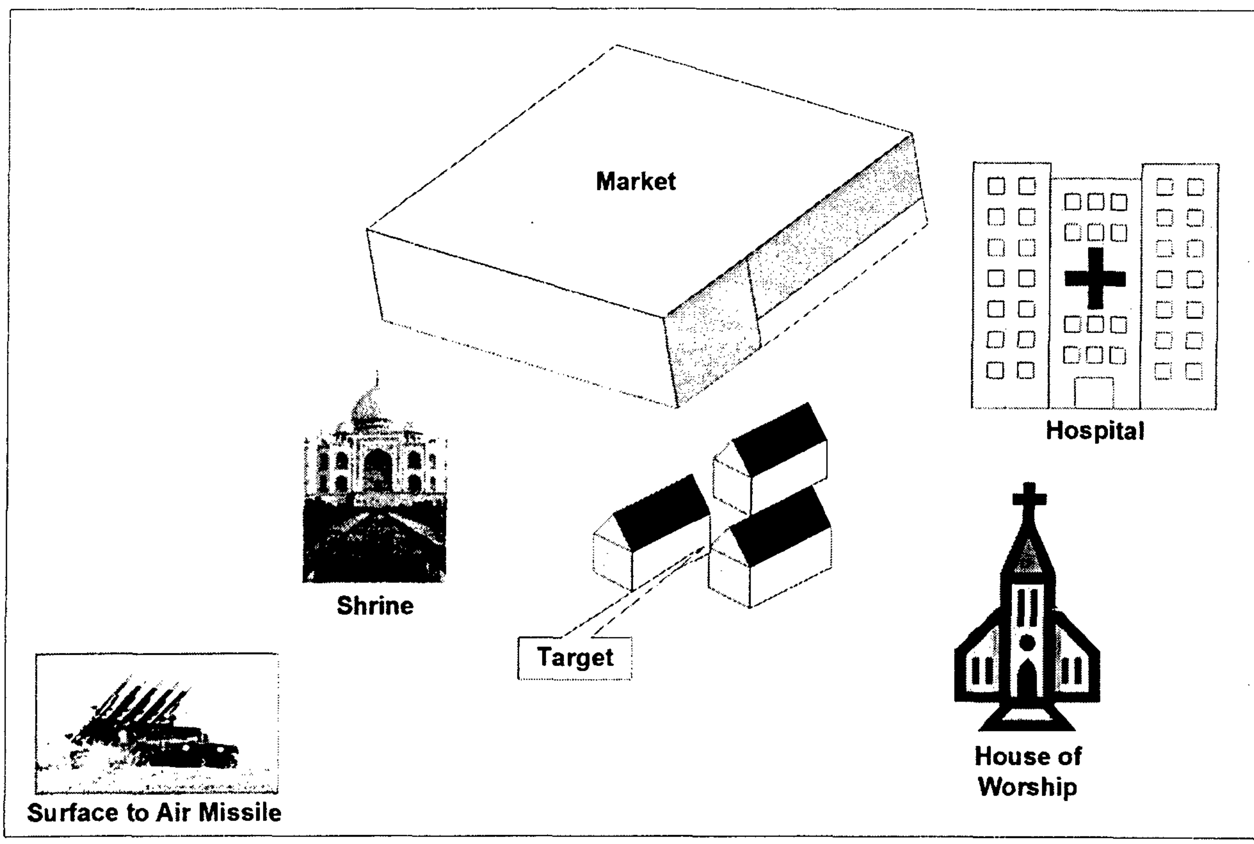

Figure 4: The target is a defended cluster of three buildings surrounded by sensitive structures

The Human-Systems Designer's Exploration of the Reasoning Space[2]

The reasoning trajectory might be initiated by review of System Mission (Figure 5). The human-systems designer might examine the relevant node and then follow the means-ends links to the level of Operational Principles & Values to become familiar with the constraining values. These are depicted as a pair of polar stars calibrated in terms of conformance to military doctrine (left) and guidance abstracted from various operational documents (right). The labels for each radial are intended as summary reminders but will not be particularly meaningful to the novice. Interrogation of a particular label will activate an embedded hyperlink leading to a succinct description (here shown as a call out, of which three are shown in Figure 5) of what that label represents (summarized from Air Force Manual 1-1, Basic Aerospace Doctrine of the United States Air Force). An even more detailed (but nevertheless still succinct) explanation may lie behind that summary statement.

The human-systems designer might then move to a review of the General Mission Functions. In a previous analysis (Lintern, 2005), I identified General Mission Functions as shown in Figure 6. To maintain global awareness, it was thought important to locate the targeting function within the overall "kill chain" that describes the general mission process (as illustrated in Figure 6). As noted in the figure, targeting is the only kill-chain function that is the responsibility of the Time Sensitive Targeting cell.

During development of this reasoning space, it became apparent that there is a characteristic (although, flexible) sequence to development of a targeting plan. That sequence, laid out in Figure 7, illustrates the strategy of first identifying the appropriate assets (with consideration to the nature of the target), of then ensuring that the spatial constraints can be satisfied, and finally ensuring that the temporal constraints can be satisfied. Figure 7 also shows the relationship of the previously identified mission functions to each of these stages. To understand the process of plan development, the human-systems designer might navigate up and down the hierarchy and visit appropriate levels of decomposition to explore the way in which each of these phases is resolved.

It may then be useful to examine the Physical Resources & Constraints nodes to overview what is available and where challenges may arise (Figure 8). As the human-systems designer checks the Physical Resources & Constraints, he or she would be able to interrogate embedded hyperlinks to access more detailed descriptions and at other times follow means-ends links to the Technical Functions & Contextual Effects (Figure 9)[3] to identify the functional capabilities or functional constraints generated by physical resources or features. The systems analyst might first examine the assets (both allied and adversary) that can be involved in an air attack mission at the physical resource level (parameters of number, location and availability) and then follow

[2] The abstraction labels "System Mission," "Operational Principles & Values," "General Mission Functions," "Technical Functions & Contextual Effects," and "Physical Resources & Constraints" referred to below correspond respectively to the labels "System Purpose," "Values & Priorities," Purpose-Related Functions," "Physical Functions & Effects," and "Physical Properties" as defined in Appendices A and B.

[3] The iconic representations in Figure 9 are discussed in the text accompanying Figure 10 through Figure 17.

the means-ends links to review the functional capabilities (range, speed, offensive and defensive capabilities) afforded by those physical properties.

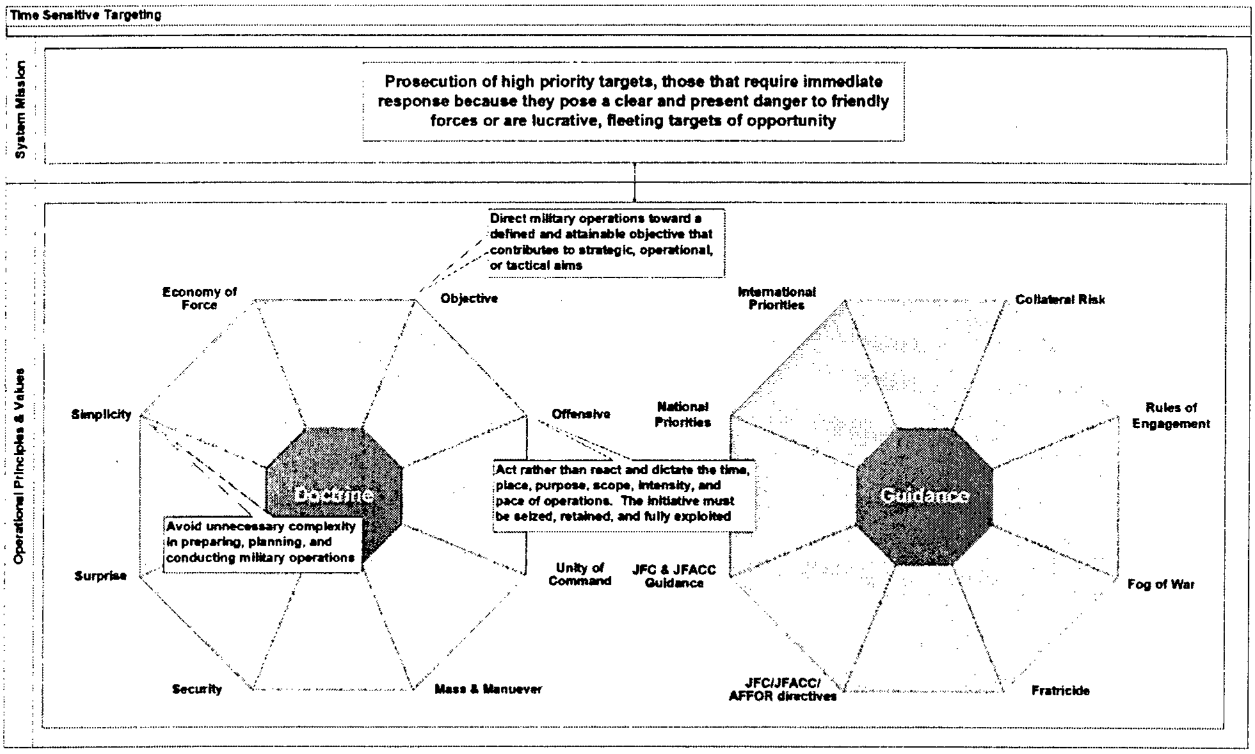

Figure 5: Purposes and Operational Principles & Values with callouts that show more detailed descriptions of selected labels

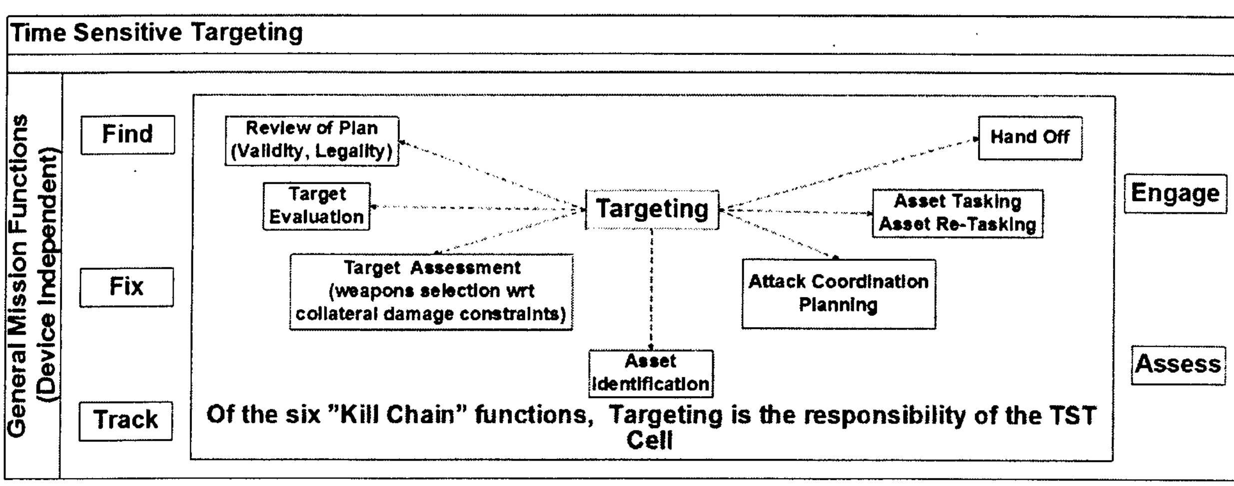

Figure 6: General Mission Functions showing the decomposition of Targeting and its relationship to other "kill chain" functions

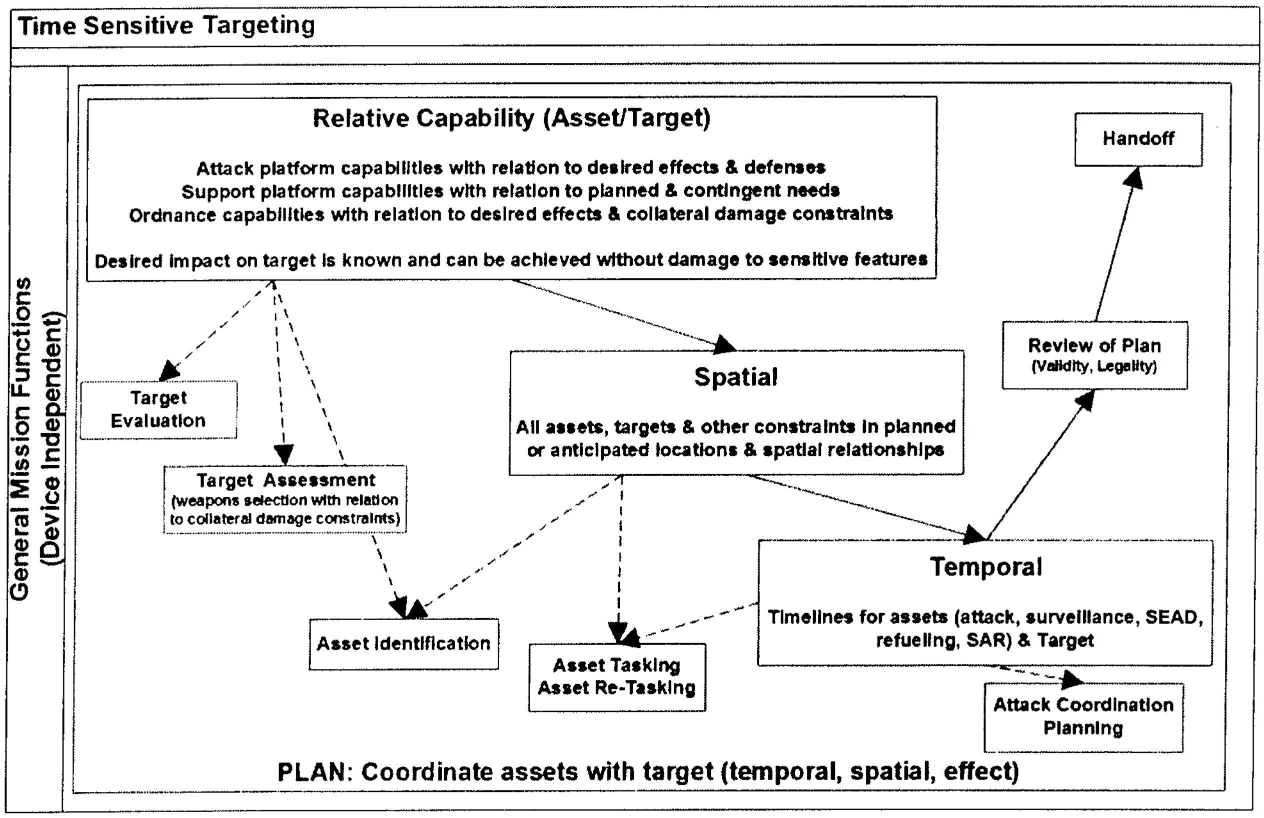

Figure 7: General Mission Functions showing a characteristic Capability→Spatial→Temporal planning sequence (solid arrows map the characteristic sequence, and the dashed arrows point to kill chain elements that participate in each stage)

During exploration at the level of Technical Functions & Contextual Effects (Figure 9), it would be necessary to examine capabilities of different technical systems and effects of different environmental systems in detail. It might be useful to start with aircraft capabilities. Figure 10 depicts aircraft range envelopes. Plan development should take account of refueling possibilities and effects on aircraft performance of winds at cruise altitude. Depictions of other aircraft functional properties have not yet been developed but samples of those that are probably important are indicated in the callouts. The two callouts are distinguished between structural and organizational properties. Interviews with subject matter experts in a previous project indicated that datalink (not currently available on all aircraft), identified in Figure 10 as Target Data Reception, offers an important support function. The voice transmission of target coordinates to aircraft is time-consuming, cognitively effortful, and error-prone. A functional capability to accept target coordinates via some form of upload reduces workload for both the targeteer and the pilot and reduces potential for error.

It would also be useful to examine the capabilities of the adversary's air assets, especially fighter aircraft that might be directed to intercept allied air assets. It would be important to become familiar with those enemy capabilities in relation to the capabilities of allied defensive and offensive systems. How, for example, do enemy fighter aircraft rate in relation to allied fighter aircraft in terms of armaments, maneuverability, and enemy detection and targeting capability?

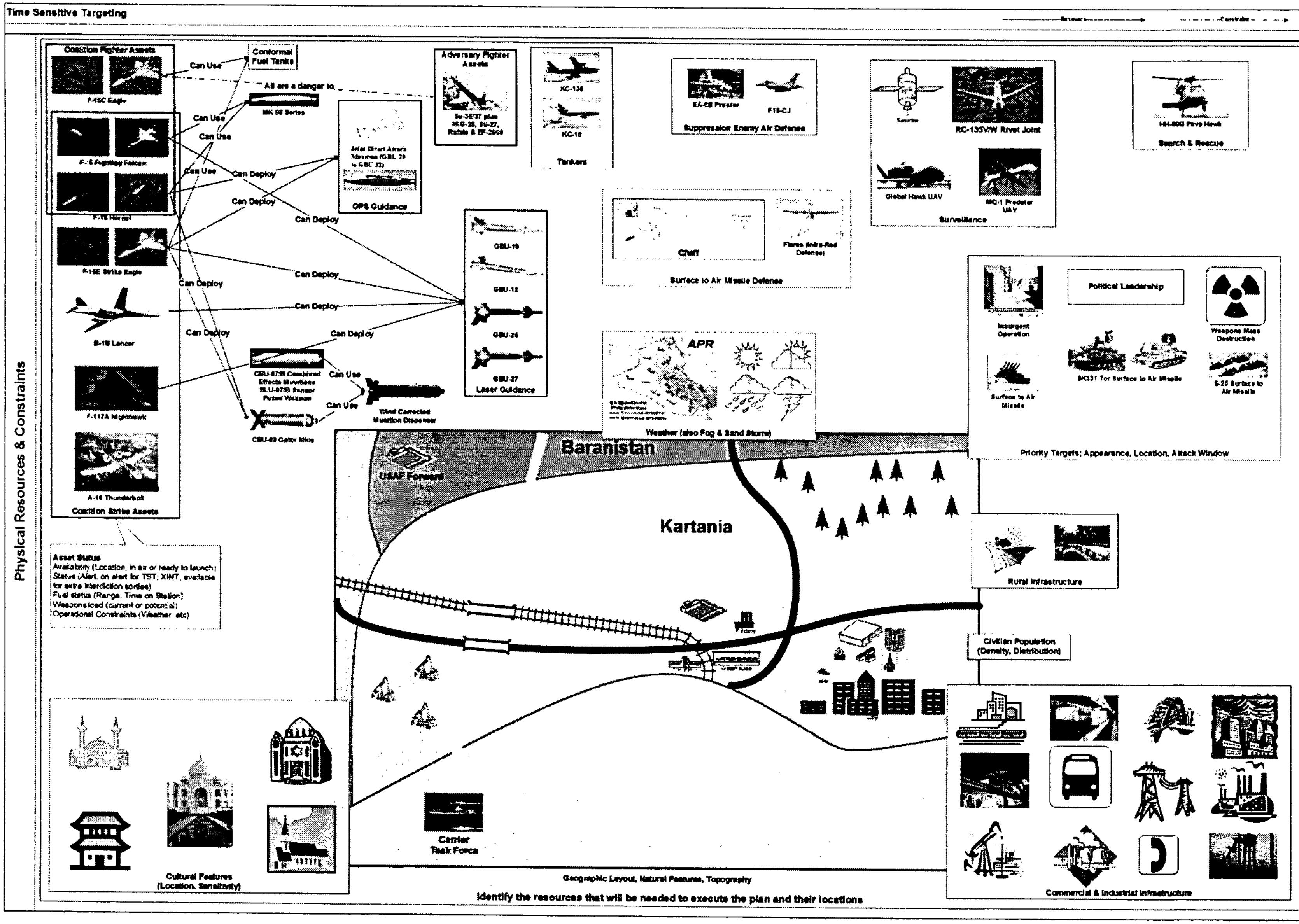

Figure 8: A layout of Physical Resources and Constraints

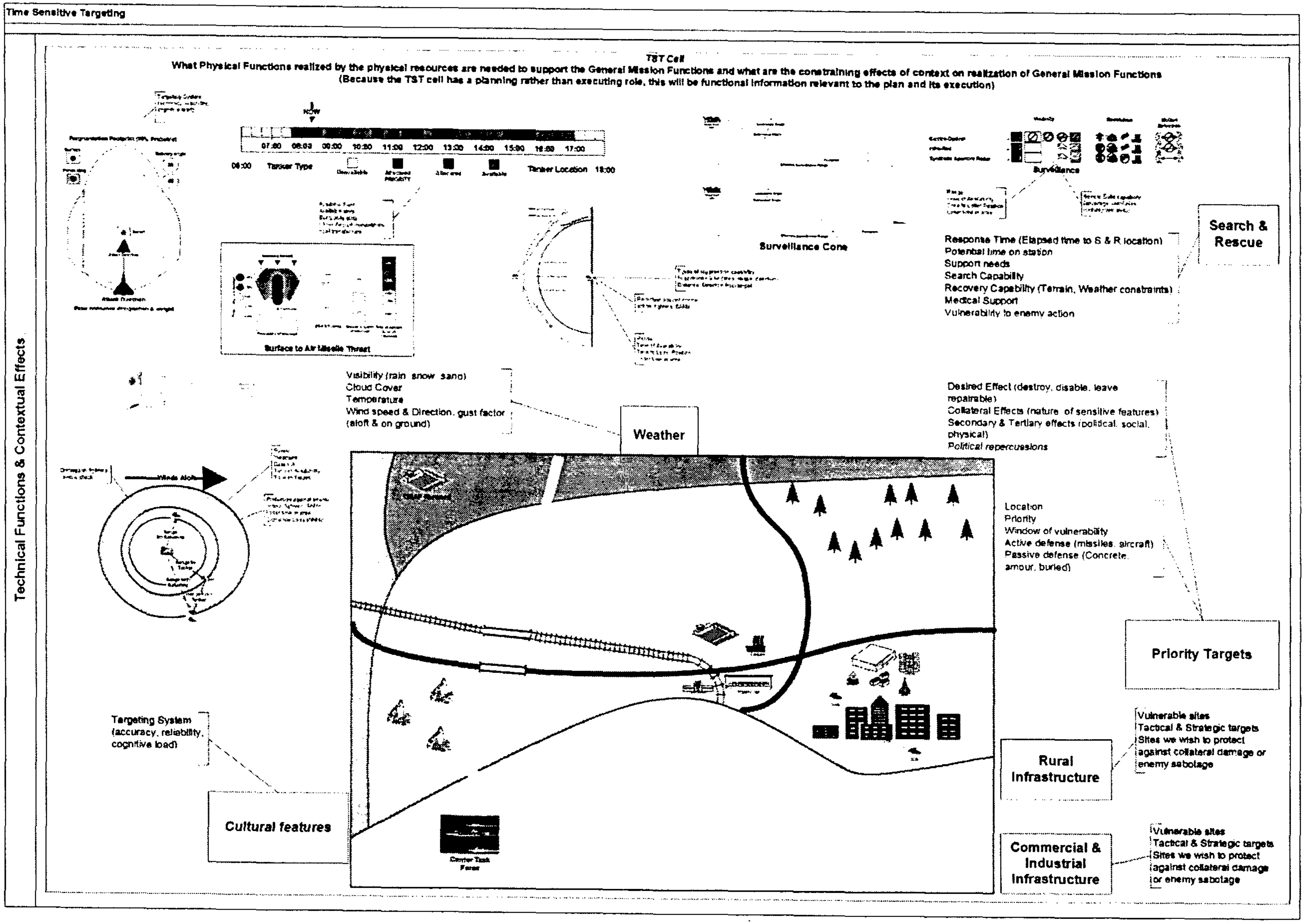

Figure 9: A layout of Technical Functions & Contextual Effects (see Figure 10–Figure 17 for clarification of illegible text)

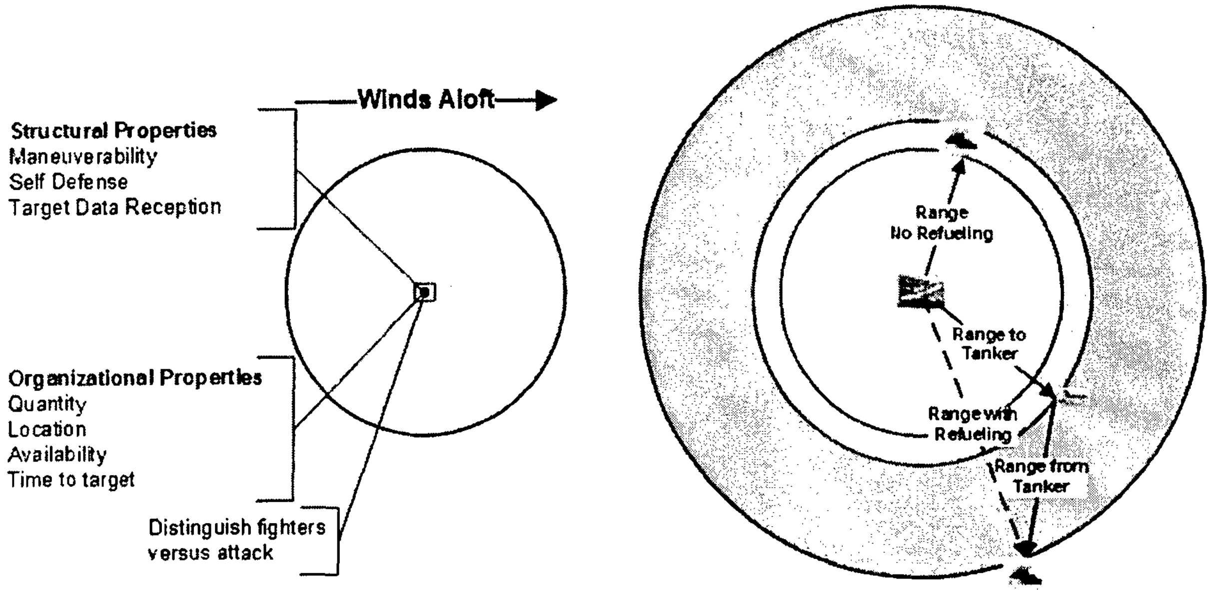

Figure 10: Left panel depicts notional aircraft range envelope (maximum range including return without refueling) and identifies other important aircraft properties for which graphical form have not yet been developed; right panel contrasts notional maximum range to target with or without refueling

Ordnance capabilities are also important. The human-systems designer would examine weapons-effect footprints at the Technical Functions & Contextual Effects level. Figure 11 shows a fragmentation footprint for a 30° versus 60° delivery angle-of-attack relative to the impact point, and distinguishes between ordnance intended for surface structures versus buried, reinforced structures. Other types of capabilities, not yet depicted in this reasoning space, would identify anti-personnel ordnance and weapons suitable for damaging aircraft runways or reinforced surface structures.

The human-systems designer might then examine the challenges posed to attacking aircraft by defensive surface-to-air missiles. The left panel of Figure 12 depicts the probability that a missile will intercept an incoming aircraft based on offset of the aircraft as it passes the missile battery. The right panel of Figure 12 depicts the risk of aircraft loss from a missile strike based on the missile velocity at intercept and the efficiency of electronic counter measures on the aircraft. Missile velocity fades rapidly with distance traveled (possibly by two-thirds over its effective range, as shown in Figure 13) once a missile reaches its maximum velocity, significantly reducing the probability first of an intercept and then of a strike with increase in distance traveled.

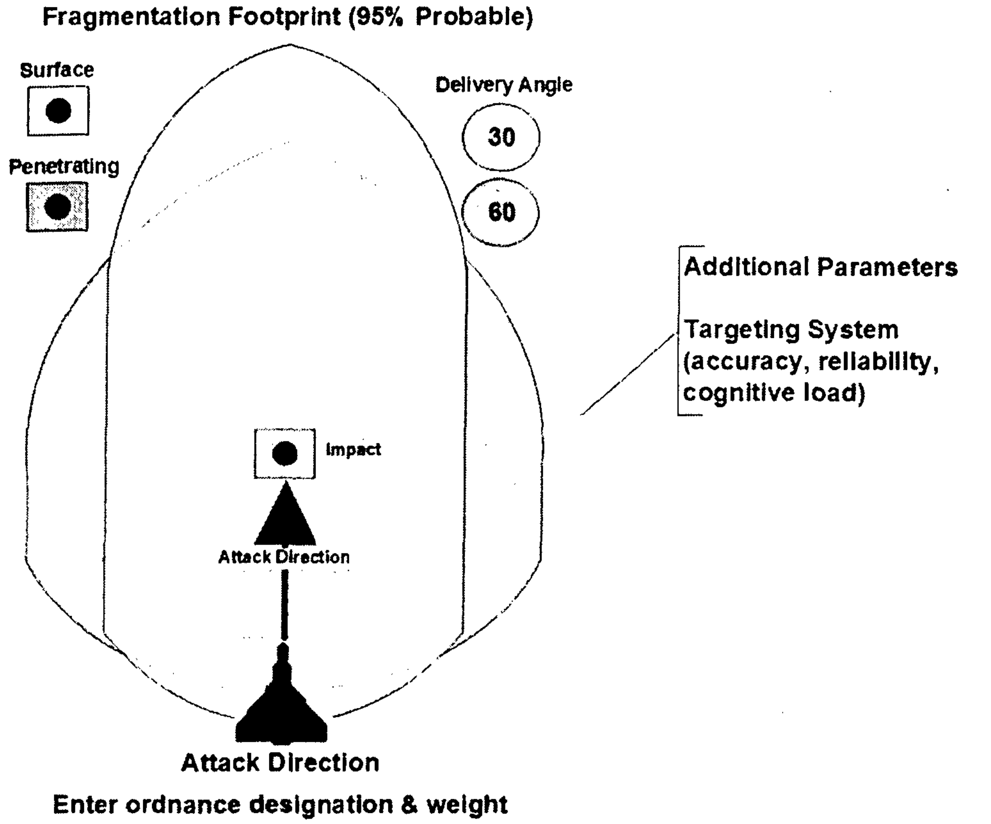

Figure 11: Notional ordnance fragmentation footprint for two delivery angles (with a suitable modeling tool, ordnance designation and weight would adjust the footprint)

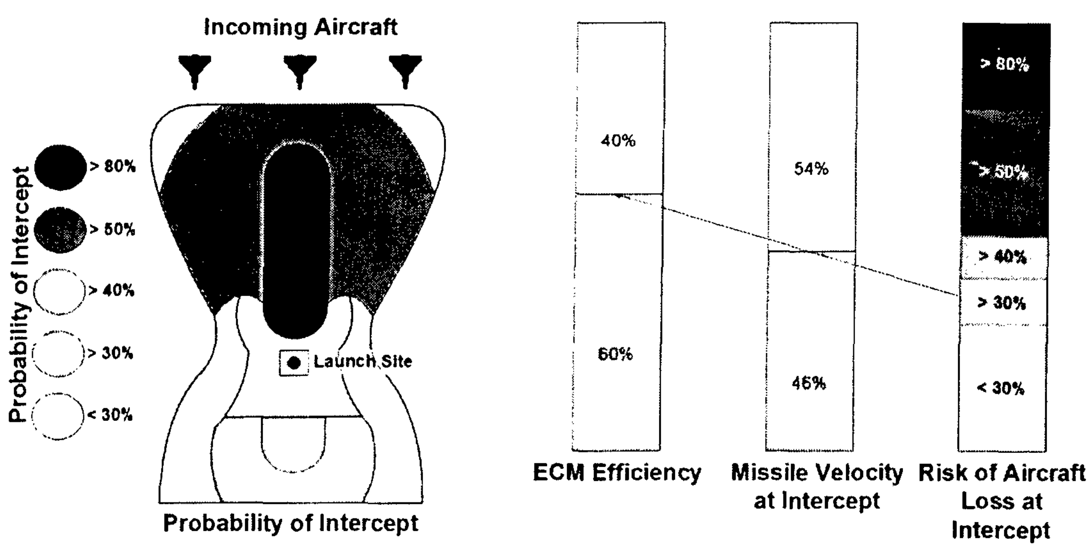

Figure 12: Notional probability of intercept of a target by a surface-to-air missile based on range and offset to incoming aircraft (left panel) and notional risk of aircraft loss from a missile strike based on missile velocity at intercept and efficiency of electronic counter measures (right panel)

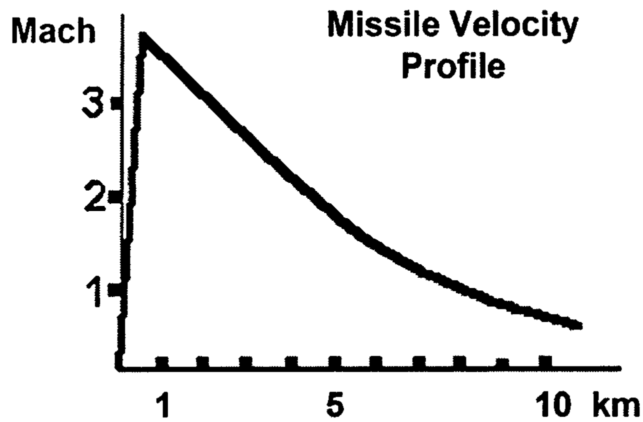

Figure 13: Illustrative velocity profile for surface-to-air missile showing speed decay versus distance traveled

Suppression of enemy air defense (SEAD) capabilities is also relevant to consideration of enemy defense capabilities. Figure 14 depicts both the radar tracking capability for a surface-to-air missile (SAM) and a jamming capability for an aircraft with enemy defense suppression capabilities. The primary lobe of the missile tracking radar is the one of most concern. Suppressive radar jamming is most effective along the axis of that lobe. Jamming effectiveness reduces with distance of the jammer from the missile radar and with offset from its primary lobe. The 99% jamming effectiveness threshold is depicted (Figure 14) as a tradeoff between distance and offset. The range of the anti-radiation missiles that the aircraft can deliver to home in on the surface-to-air missile radar is also depicted. As shown here, it is desirable that the defense suppression aircraft stand outside the primary acquisition range of the missile. As depicted in Figure 14, a 30° jamming cone from that range lies within the 99% jamming effectiveness threshold to reveal that effective jamming is possible from that distance if the standard 30° jamming cone is used.

Most missions will require air refueling. Tanker resources are typically in demand and so the development of a refueling schedule for a mission with many extra aircraft can be demanding and time-consuming. The graphic of Figure 15 shows a 12-hour tanker timeline in which 20-minute slots are shown as available, allocated, priority allocated, or unavailable. While any allocated slot can be reallocated to a higher priority requirement, a priority icon attached to an allocated slot offers a caution that this slot has already been allocated to a high priority requirement. Unavailable slots indicate the times that a tanker is not on its refueling station.

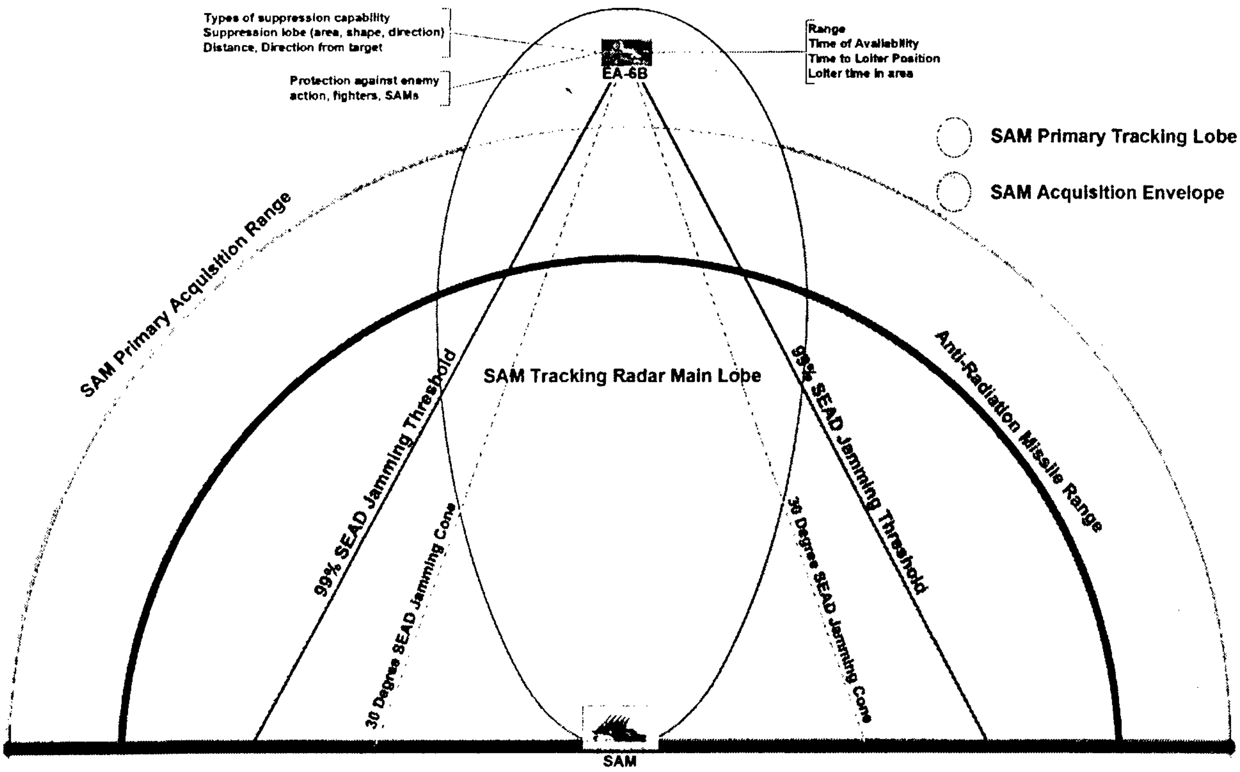

Figure 14: A notional comparison of target acquisition range for a surface-to-air missile and the target detection lobe of its radar versus an air borne electronic suppression capability and range of an air delivered anti-radiation missile

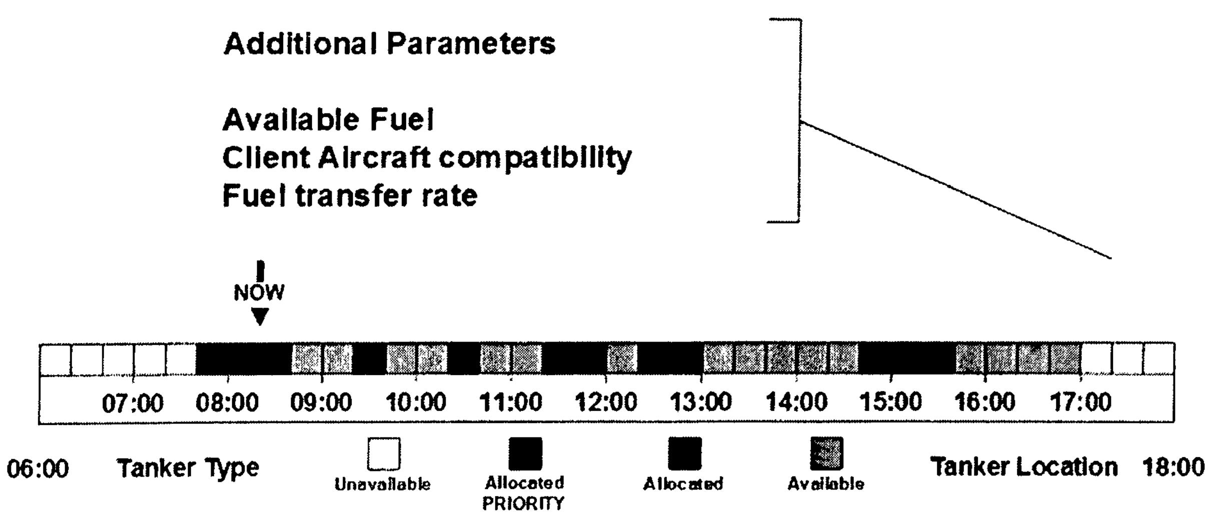

Figure 15: A notional tanker scheduling timeline

Figure 16 depicts the capabilities of three types of airborne surveillance sensors in terms of their effectiveness in different visibility conditions, the size of objects they can resolve and whether or not they can detect motion. Figure 17 shows the surveillance range and footprint as impacted by the subtended angle of the surveillance cone and the lookdown angle. The upper panel in this figure shows a surveillance footprint within the effective surveillance range. In the lower panel, the footprint extends beyond the effective surveillance range, suggesting that some adjustment in the surveillance parameters is desirable. Possibly there would be some benefit in reducing subtended angle of coverage to enhance resolution or it may be desirable to decrease standoff range to ensure that the entire footprint is within the effective surveillance range.

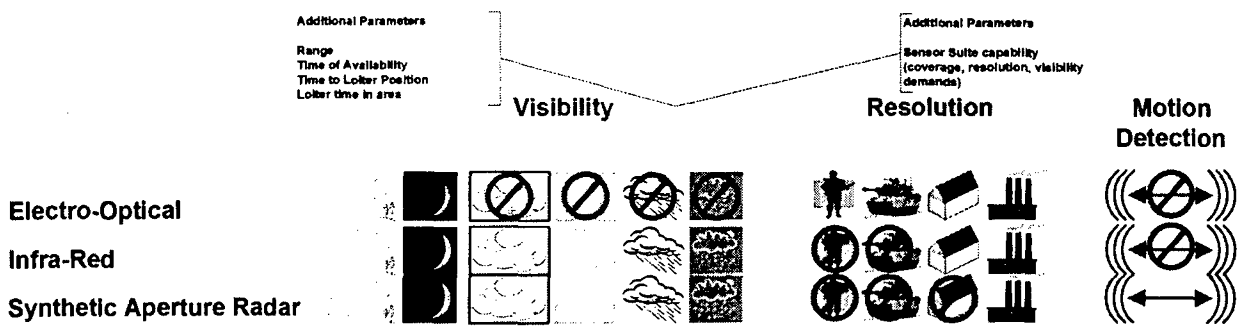

Figure 16: Functional capabilities of different surveillance systems in terms of detection capability under different visibility conditions, resolution capability for different sized objects and motion detection capability

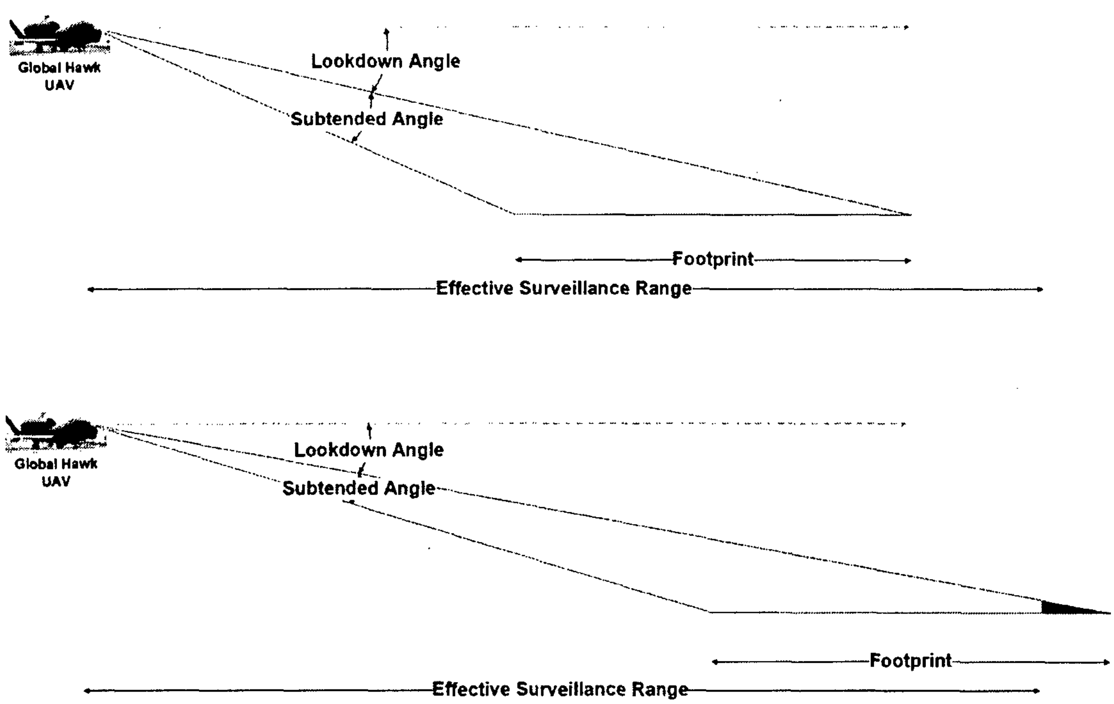

Figure 17: Surveillance cone for airborne system illustrating range and footprint as impacted by the subtended angle of the surveillance cone and the lookdown angle (upper panel shows footprint within range; lower panel show footprint extending beyond range)

Once the human-systems designer has reviewed the functional capabilities of technical systems, he or she might review general weather patterns that could impact operations. Weather forecasting is one of the few areas relevant to this domain in which there has been considerable progress in developing innovative and evocative visualizations. Because the review of that material would require a major effort and was not the primary goal for this project, an effective visualization of weather and its effects have been left for the future.

The human-systems designer might then examine priority target types and also commercial, industrial, social and cultural structures that could potentially influence a targeting plan. The left panel of Figure 18 shows icons that could be used to represent high-priority targets. The middle panel has icons for commercial and industrial infrastructure; systems that under some scenarios will be viewed as targets and under other scenarios will be viewed as sensitive structures that should not be damaged. The right panel has icons for cultural and religious structures that should not be damaged under any scenario.

The human-systems designer should not yet need to review specific numbers and locations of objects of different types (or specific weather forecasts for particular periods) but should become familiar with the types of issues that might be encountered during planning. Particularly with generic target types, he or she might consult linked documents to assess special characteristics that may be of interest in terms of their vulnerability to different types of weapons, preferred targeting locations, and expected or desired effects of a strike against them.

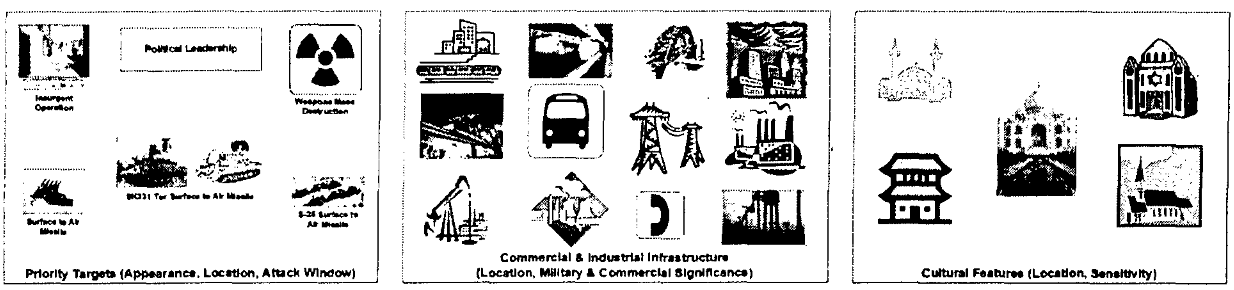

Figure 18: Priority target types and also commercial, industrial, social and cultural, structures that could potentially be designated as sensitive and to be protected against collateral damage

It may be useful, for example, for the human-systems designer to be aware that the type of structure and the constituent materials of a bridge to be targeted for destruction. This can impact the targeting plan because they determine the bridge's vulnerability to damage or destruction. Challenges confronting replacement of that bridge can also impact targeting decisions in the event that our own forces might want to use it in the near future, or if its reconstruction would be part of a future rebuilding program. A desire to temporarily disable rather than destroy a bridge would impact the choice of ordnance.

The functional constraints imposed on targeting by some physical features such as houses of worship, shrines, or community centers may be self-evident from the physical appearance or their identifying title. It may seem overly pedantic to identify functions of objects such as a hospital when they seem so obviously implied by its name, but the functions of many other physical features are obscure and it is essential within this reasoning structure to maintain consistency within and across levels of abstraction. In particular, the inclusion of obvious relationships provides intuitive illustrations of how to use the reasoning space, while omission of those obvious relationships can potentially generate confusion about how it works.

Concerns about collateral damage to sensitive features would flow from statements in guidance documents about protection of non-combatants, cultural sensitivities, and adherence to international law. Many of these concerns may also seem obvious (for example, is it necessary to point out that we should not indiscriminately place non-combatants at risk?) but consistency within and across levels of abstraction is crucial at all levels. Furthermore, even self-evident concerns can diminish in significance during the heat of combat.

At this stage, the human-systems designer would know a good deal about the resources and constraints related to planning for time sensitive targeting. To enrich and extend his or her knowledge and to make it more robust, it would now be useful to embark on a planning exercise.

A PLANNING TRAJECTORY FOR A HUMAN-SYSTEMS DESIGNER

This section illustrates how a human-systems designer or analyst might use a scenario and the reasoning space to determine the nature of the work conducted by planners in a Time Sensitive Targeting cell. Possibilities for tuning the reasoning space for those who are to work as Air Operations staff should also become clearer as one reads through the exercise illustrated here.

The exercise to be described is aimed at development of a targeting plan for the scenario described in the earlier **Targeting Scenario** section of this report. The human-systems designer or analyst acts as a planner within a Time Sensitive Targeting cell. He or she starts by examining the general layout of the area of operations (Figure 3), the general topography, the locations and general layout of cities, and the locations and layout of major industrial, commercial and public infrastructure. He or she would then commence to work through a process similar to that undertaken by a planner within a Time Sensitive Targeting cell.

Functional Coordination

Military resources have functional capabilities and part of the planning challenge tackled by a targeteer is to ensure that the allied capabilities committed to the mission have the functionality required not only to fulfill their role in the mission but also to counter any functional capabilities the adversary might use to disrupt the mission. Nonmilitary features, on the other hand, can be either resources (e.g., distinctive features can be used to guide a strike pilot to a target) or constraints (e.g., weather effects can restrict options or sensitive structures can limit the nature of a strike).

Once a target is identified, delivery options would be reviewed and a selection made. Guided missiles or high-level bombers are possibilities, but for this exercise accuracy is deemed important, so a piloted aircraft that will permit visual sighting of the target area during the attack run is required. Because the target area lies within potentially hostile territory, a high-speed, long-range platform with the ability to outmaneuver enemy aircraft and to counter surface-to-air missiles will be used. While the A-10 Thunderbolt can carry suitable ordnance, its performance profile is unsuitable for this mission. A B-1B Lancer would be effective but to deploy it for an isolated target would be an inefficient use of a scarce resource, as would the use of an F-117A Nighthawk. Both the F-15E Strike Eagle and the F-18 Hornet have suitable performance profiles and can carry suitable ordnance. The decision is made to schedule one of those aircraft types for the mission.[4]

To select a suitable weapon, the human-systems designer, acting as a planner, would locate and identify the target, examine its physical characteristics and consider the desired effect of the strike against it. The target is a non-reinforced surface structure that is to be demolished. The destructive effect of the available ordnance would be assessed via the depiction of fragmentation footprints (Figure 11) at the level of Technical Functions & Contextual Effects to confirm this selection. That fragmentation footprint, when laid over the target area at the General Mission Function level, suggests that a 2,000-pound warhead would offer suitable destructive capability (Figure 19, left panel). This leads to selection of a 2,000-pound MK-84 general-purpose bomb.

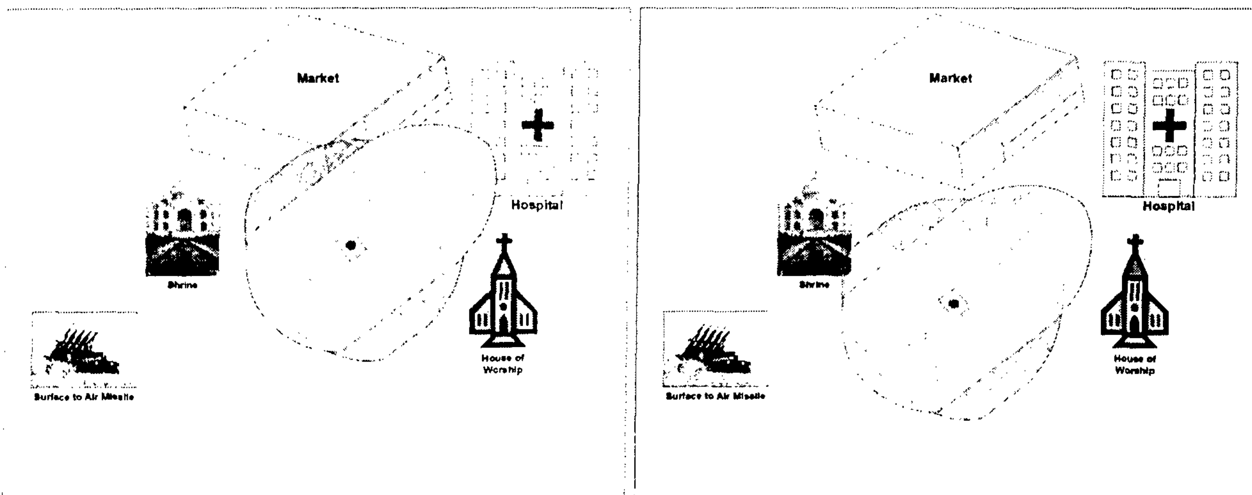

Figure 19: The target area overlaid with an ordnance fragmentation footprint for two delivery angles with left panel showing unacceptable risk of collateral damage which is corrected in the right panel by adjustment of ordnance impact point and selection of a 30-degree delivery angle

Previous work (Lintern, 2006) has shown that a planner will often assess issues related to collateral damage early in planning by examining the physical layout of the space surrounding the target to identify sensitive structures or social environments that must be protected. In this case, the human-systems designer acting as a planner ascertains that the targeted area is surrounded by several sensitive structures (Figure 4). The functions of these structures are obvious, but could be confirmed by tracing the means-ends links between the levels of Physical Resources & Constraints and Technical Functions & Contextual Effects. The fact that these are sensitive structures that should be protected from collateral damage is also obvious, but could be confirmed by tracing the means-ends links through the General Mission Functions to the level of

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[4] For reasons discussed later, access to further details of aircraft resources is described in a later section of this report, headed **Resource Descriptions via Embedded Hyperlinks**

Operational Principles & Values to access relevant instructions, guidance, and rules of engagement.

The potential for unacceptable collateral damage requires further thought about the destructive effects of the ordnance and its fragmentation footprint. An approach heading of 050° (to approach the target from 230°) is selected initially, but it is apparent from inspection of Figure 19 (left panel) that the fragmentation footprint of the selected ordnance overlaps some of the sensitive surrounding structures. One option might be the evaluation of whether less destructive ordnance would damage the target sufficiently. However for this scenario illustration, the option pursued is reassessment of the weapon delivery direction and angle of attack, which also influences the fragmentation footprint. Two fragmentation footprints are shown, one based on a 30° angle of delivery and the other on a 60° angle of delivery. Both delivery angles show an unacceptable risk of collateral damage, the fragmentation footprint for the 30° angle overlapping the hospital and at that for the 60° angle overlapping the market.

Although the most desirable impact point from a target destruction point of view is in the center of the cluster of three buildings, total target destruction can be achieved even if it is displaced slightly. The adjustment shown in Figure 19 (right panel) clears both footprints from the market and the hospital. However, the footprint for the 60° delivery does not cover the targeted structures entirely and now impinges on another sensitive structure, the shrine. Thus a 30° angle of delivery is selected for the adjusted impact point.

The fit is tight however, so reliability and accuracy are imperative. Thus a guided weapon is required. Both the F-15E Strike Eagle and the F-18 Hornet can deliver bombs guided by the Global Positioning System or by laser. The target itself is easily distinguished from the surround, so laser-guidance (as provided by the Guided Bomb Unit-24, which can be fitted to the MK-84 general-purpose bomb as shown in Figure 8) is preferred over Global Positioning System guidance because the pilot will be able to ensure visually that the weapon is aimed at the right structure. The pilot will need a clear and unambiguous description of the target and of distinguishing landmarks for visual tracking onto the target. Landmarks that can guide the pilot to the target should be sufficiently visible so that pilot workload is maintained within a reasonable level.

The use of laser-guidance is further encouraged by the forecast for the critical period, which is for excellent air-to-ground visibility. Any possibility of extensive cloud cover would require an adjustment of this plan to guidance by Global Positioning. Because dense cloud cover is common in the attack area for this time of year (as assessed by examination of weather effects at the level of Technical Functions & Contextual Effects), there is some concern about reliance on laser guidance. This issue is resolved by ensuring that two attack aircraft that carry bombs guided by the Global Positioning System (Figure 8 shows that a MK-84 general-purpose bomb can be fitted with a Guided Bomb Unit-32) are in the vicinity, ready to be tasked for the attack at the last moment. Aircraft with data-link capability are preferred for this backup role to avoid the need for the time-consuming and error-prone procedure of transmitting target coordinates by voice link.

The analyst acting as a planner should notice that the target (in addition to being nestled within sensitive structures) is located near a defensive missile site and the selected approach to the target passes near it. He or she might reconsider the direction of approach but cannot avoid significant collateral damage from any other approach course except the reciprocal approach heading of 230°, which only transfers the problem from target approach to target egress. (A decision about whether one is more desirable than the other is the sort of issue that should be easily resolved within this reasoning space but, as with many other relevant issues, the appropriate subject matter expertise has not yet been acquired.)

A depiction of the hostile surface-to-air missile capability at the Mission Function level reveals a potential danger for allied strike aircraft (Figure 20). The proximity of the target area (and especially the F-15 attack course) to a hostile surface-to-air missile site suggests the need for suppression of enemy air defense capability. This functional capability can be found at the Physical Function level and means-ends links can be followed from there to the Physical Resource level to identify the aircraft types that can provide this functional capability. The detection lobe of the missile radar and the missile range should be examined at the Physical Function level (Figure 14) and then compared at the Mission Function level (Figure 20) to the suppression capabilities of the selected Electronic Warfare aircraft when standing off outside the surface-to-air missile range.

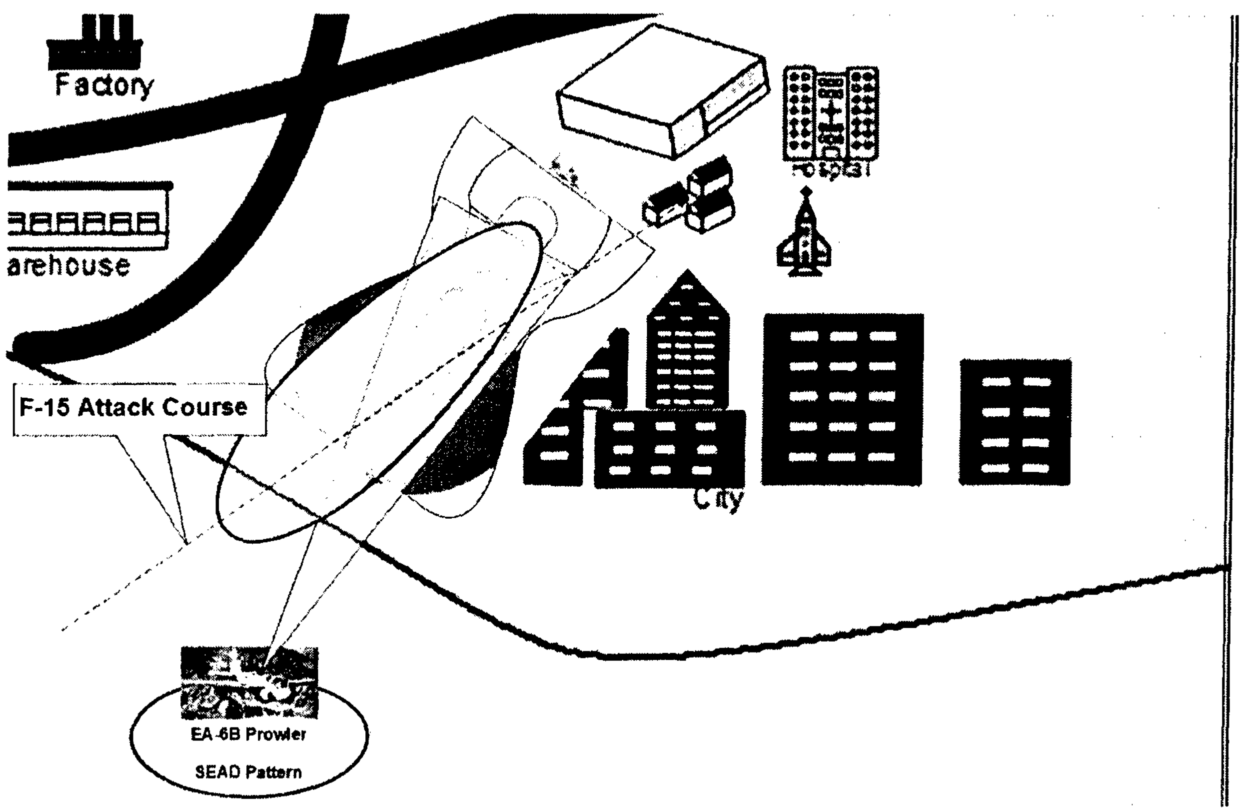

Figure 20: F-15 attack course in comparison to SAM kill zone, SAM radar primary lobe and SEAD suppression lobe

An EA-6B Prowler is selected as an appropriate aircraft currently operating in the theater that would be suitable. This aircraft carries anti-radiation missiles that can home in on the surface-to-air missile radar. However, because the range of that anti-radiation missile lies within the primary acquisition range of the surface-to-air missile, the use of the anti-radiation missile in this circumstance is not recommended. The Prowler will be assigned to a station beyond the surface-to-air missile range, but located along the line of the attack to ensure optimum jamming as the radar main lobe is directed at the attacking aircraft (Figure 20).

The adversary has a small Air Force with some fighter aircraft that could disrupt this mission. To guard against that possibility, the mission plan will include the scheduling of fighter cover for all other aircraft involved in the mission. It is known that the adversary has several Russian SU-27s, which are thought to have an edge in maneuverability over the F-15 (a suitable depiction of this comparison has not yet been developed). Because of that, the F-18 Hornet will be preferred for this role.

The plan calls for continued surveillance of the insurgency meeting site. The human intelligence assets that first learned of the meeting will continue to observe the site and report back when possible, but there is a need for assets that can report back in real time as they monitor the site. The surveillance function at the Physical Function level is linked to suitable surveillance assets at the Physical Resource level. The Global Hawk offers suitable capability. It has an optical surveillance capability to permit visual identification in good weather and a Synthetic Aperture Radar and infrared capability to infer arrival and departure of vehicles if the optical sensing system is obscured by unfavorable weather conditions. A Global Hawk will be scheduled to maintain the target area under constant surveillance (Figure 21).

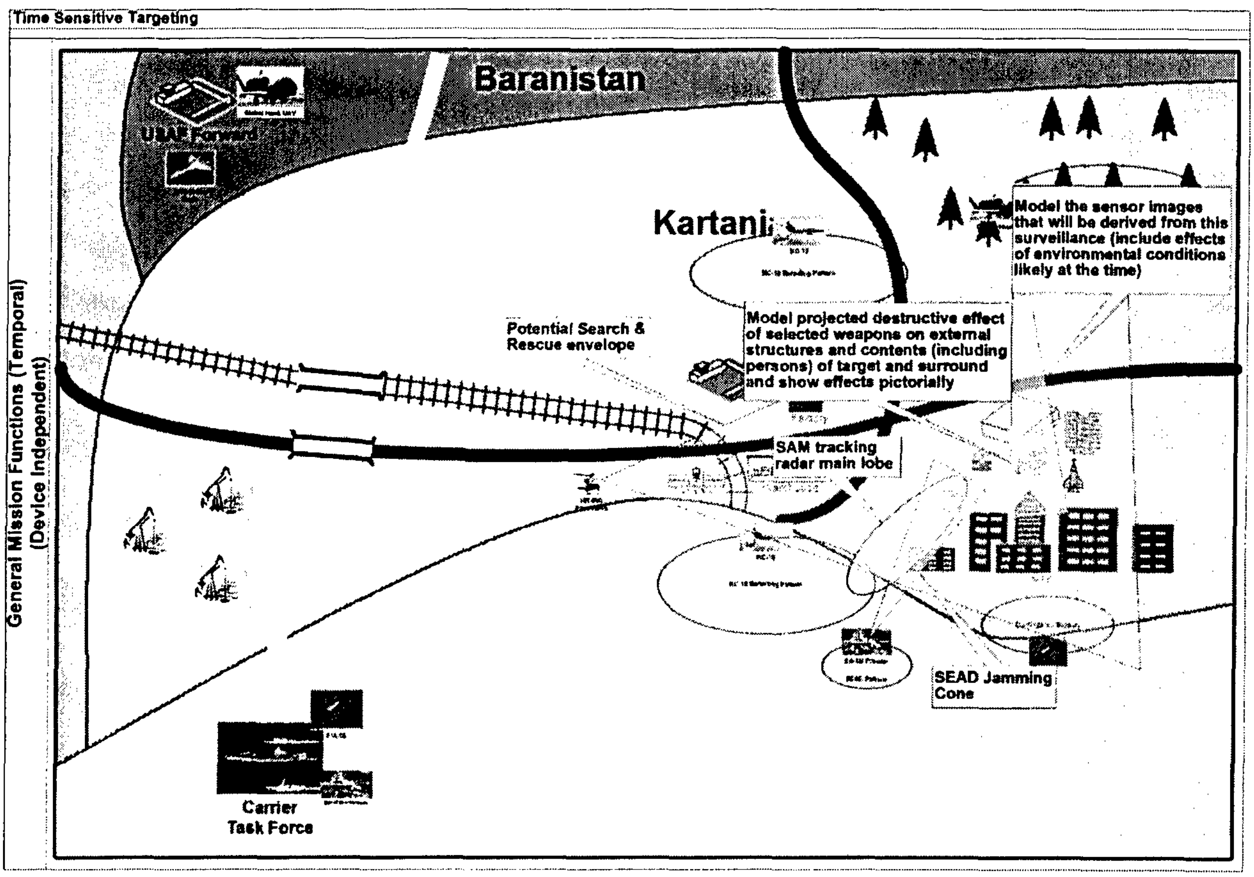

Figure 21: Critical mission functions

Search and rescue assets will be scheduled to wait at an appropriate location to rescue airmen in case an aircraft is lost. The HH-60G Pave Hawk is identified as the appropriate asset for this task. Its equipment includes a personnel locating system compatible with the PRC-112 survival radio carried by airmen that provides range and bearing information to a survivor's location. It has a hoist capable of retrieving two to three airmen from a hover height of 200 feet, thereby obviating the necessity to land during a rescue mission. It carries surface-to-air countermeasures that could be needed in this scenario environment. Finally, it has an in-flight refueling capability that may be needed if the search and recovery mission extends over a period of time, and it has light offensive capability in the form of 7.62-mm machine guns that could be brought to bear against ground troops during a recovery.

Spatial Coordination

It is now necessary to identify specific assets for the coordinated strike (tail numbers). Once aircraft types have been identified, their hyperlinks can be interrogated to bring up documents that identify their home locations, their tail numbers, and their availability for this mission.

For this scenario, suitable air assets are available in both the carrier task force off the south coast of Kartania and the USAF forward air base in Baranistan (Figure 21), but the carrier task force is closer to the target area and its resources are preferred. Nevertheless, interrogation of the air asset hyperlinks reveal that the strike aircraft (F-18 Hornets) from the carrier task force are otherwise committed at the required time so—while an EA-6B Prowler for Suppression of Enemy Air defense and F-18 Hornets for fighter cover will be scheduled from the carrier task force—the strike aircraft (F-15E Strike Eagle) will be scheduled from the USAF forward air base in Baranistan. A planner might consider submitting a request to re-task the carrier strike assets to this mission, but subject matter experts consulted for other projects have stated that they are generally reluctant to make such requests.

Range and endurance envelopes are examined for all selected aircraft at the Physical Function level (Figure 10) and then overlaid on the area of interest map to assess whether the selected aircraft can reach their respective operational areas and return safely. In this scenario, all strike and fighter aircraft must refuel at least once. Refueling functions are found at the Physical Function level and followed to the Physical Resource level to identify tankers that might satisfy this requirement. Hyperlinks from the tanker resources show what refueling resources are available and the locations of refueling stations. There are two KC-10 refueling stations that could be used in this scenario; one in north-central Kartania and one off the south coast of Kartania.

Figure 22 illustrates the use of range overlays for the F-15s flying out of the USAF Forward base in Baranistan. The overlay centered on the USAF Forward base reveals that the F-15s cannot directly reach either the target or the tanker station off the south coast of Kartania, but must refuel at the tanker station in central Kartania. The overlay centered on the tanker station in central Kartania reveals that they cannot return to that station from the target, but must refuel again at the tanker station off the south coast of Kartania. They can then reach the target and refuel at the tanker station in central Kartania on the way back to the USAF Forward base. Similar use of a range overlay would reveal that the fighter aircraft (F-18 Hornet) from the

Carrier Task Force must refuel once on the way to the assigned loiter area, and once on the way back.

The Global Hawk that routinely traverses the northern boundary of the operational area is seen to be one that can be tasked for this job. The unmanned aerial vehicle is to be diverted from its regular route to maintain surveillance over the meeting site. Its surveillance coverage capability will be checked at the Physical Function level and then compared to the spatial layout of the target at the Mission Function level to determine a standoff range for surveillance and to ensure the surveillance flight pattern is safe for the vehicle and secure from observation by those who might warn the insurgents (Figure 21).

An examination of tail numbers at the Physical Function level of the required Search and Rescue aircraft (the HH-60G Pave Hawk) reveals that one is available from the air asset inventory of the carrier task force. It will take up a station for the duration of the operation approximately 150 km west of the target in a sparsely populated area of Kartania (Figure 21) to be readily available for a rescue mission. Its mission station will be close to an in-flight refueling station and it will be required to refuel before it takes up station and to then set down in a safe area to await the outcome of the mission. The selected mission station is one that permits ready access to the area in which pilots would be at risk if they were to eject from their aircraft, as shown by the potential Search and Rescue envelope in Figure 21.

Temporal Coordination

Once all functions and specific assets have been identified, the timing of the mission is addressed at the General Mission Function level by backtracking from scheduled time over target. Those timelines take account of traversal time, in-flight refueling time, and time of arrival on station. All assets have a requirement to be on station in advance of the scheduled attack time, and the requirements differ for the various assets. Refueling slots must be reserved at the necessary times, and aircraft must be scheduled to commence their operation in time to reach their assigned locations at critical times. Figure 23 (also see Figure 24) shows timelines for all assets at critical locations such as air refueling stations. The crucial requirement is to have all assets at their assigned stations for the strike. Temporal coordination requires some care and the plan must ensure that temporal demands are not placed on assets that will compromise their fuel resources.

The timelines are linked to individual assets to ensure that the scheduling of that asset at various locations is consistent with its availability and the mission demand. Timelines are also inter-linked globally at strike time to ensure that the plan has all assets properly coordinated as follows:

- Strike aircraft are to be in a loiter area 15 minutes from the target at 0945, off the coast or within an area identified as having no insurgent sympathizers who might trigger a suspicion of allied intent.
- Timing of air-refueling requirements with an estimated latest-time-of-attack at 1045 hours to ensure all aircraft have sufficient fuel to remain on station for the required time.
- Search and rescue is to be on station from 0930 hours to 1130 hours with contingency plans ready to rescue downed aircrew in the target approach area, the target area, and the target exit area. In the case of downed aircrew, the unmanned aerial vehicle will be re-tasked to aid the search and rescue effort.

- Air surveillance is to commence at 0900 and continue through to 1200.
- The unmanned air vehicle will monitor the arrival of the insurgents.
- The strike will nominally be scheduled for 30 minutes after scheduled start time for the meeting but this element of the plan will be subject to real-time adjustment. The strike will be called in earlier if surveillance can confirm that the important members of the insurgency leadership team have arrived, or if there are indications that the meeting is breaking up early. In the event that surveillance cannot identify the leaders as they arrive and cannot determine whether all have arrived, the strike will proceed at 30 minutes after the scheduled start time for the meeting. In the event of inclement weather that prevents visual monitoring, infrared surveillance will be available as a backup.
- The missile battery must be suppressed just prior to the attack, so Electronic Warfare aircraft will need to be situated to move readily into position just before the strike aircraft are to reach the target area. The kill envelope of the missile will be examined to ensure that radar suppression commences just before the strike aircraft enter it.

Air refueling is the most complicated of the temporal coordination requirements. In this scenario, there are two refueling locations but only one is convenient for the Carrier Task Force assets and it also must be used to refuel the strike assets from the USAF Forward Base in Baranistan prior to the attack. In addition, aircraft on other missions will also use those refueling assets, so that some of the refueling slots will most likely be already committed at the time of mission planning. Since this is a high-priority mission it would be possible to bump other refueling assignments to make way for this mission's refueling requirements, but subject matter experts indicate that they typically avoid bumping other aircraft already assigned to refueling slots unless that cannot be avoided.

Plan Review

Once the plan is complete, it is reviewed for overall consistency and viability. At this point, the human-systems designer or analyst will take on the role of the Time Sensitive Targeting cell chief who will check the plan and will release it if satisfied. The cell chief will pay particular attention to Operational Principles and Values to ensure that the plan conforms to doctrine and guidance. The cell chief will apply qualitative judgments to that task. Figure 25 illustrates a scenario in which the cell chief is generally satisfied, but remains concerned about the possibility of unacceptable collateral damage. There may be consultation between the cell chief and the representative of the Judge Advocate General. They may follow a hyperlink from the relevant spoke to a summary of issues to investigate whether a strike proximal to a number of sensitive structures of these types is warranted for the nature of this target.

The polar star format shown in Figure 25 is often used in systems in which value parameters, measured by technological means, are used to adjust the lengths of the radials automatically. At this stage in the development of this reasoning space, it is unclear that automatic adjustment is either possible or desirable. Rather, the human-systems designer or analyst might introduce an asymmetry manually when one member of a collaborative team notices an issue. That asymmetry will serve as a reminder or as an alert, and will be corrected when members of the collaborative team have dealt with the issue. In actual planning for Time Sensitive Targeting, it might be set as asymmetric by a cell chief who, being dissatisfied with the elements of a plan bearing on that value, wants to alert the targeteer to the need to revise certain of its elements.

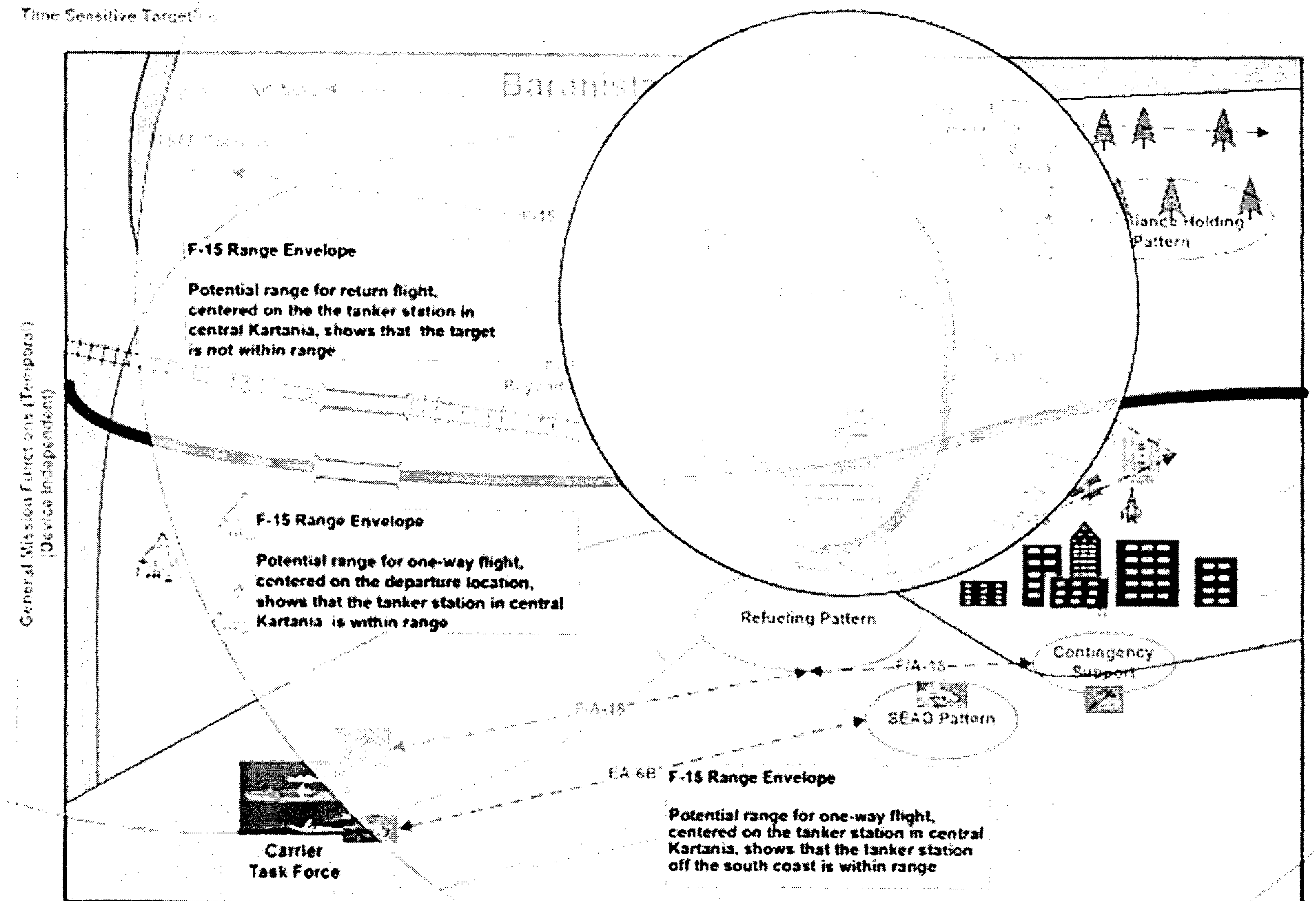

Figure 22: The use of range rings to establish refueling requirements

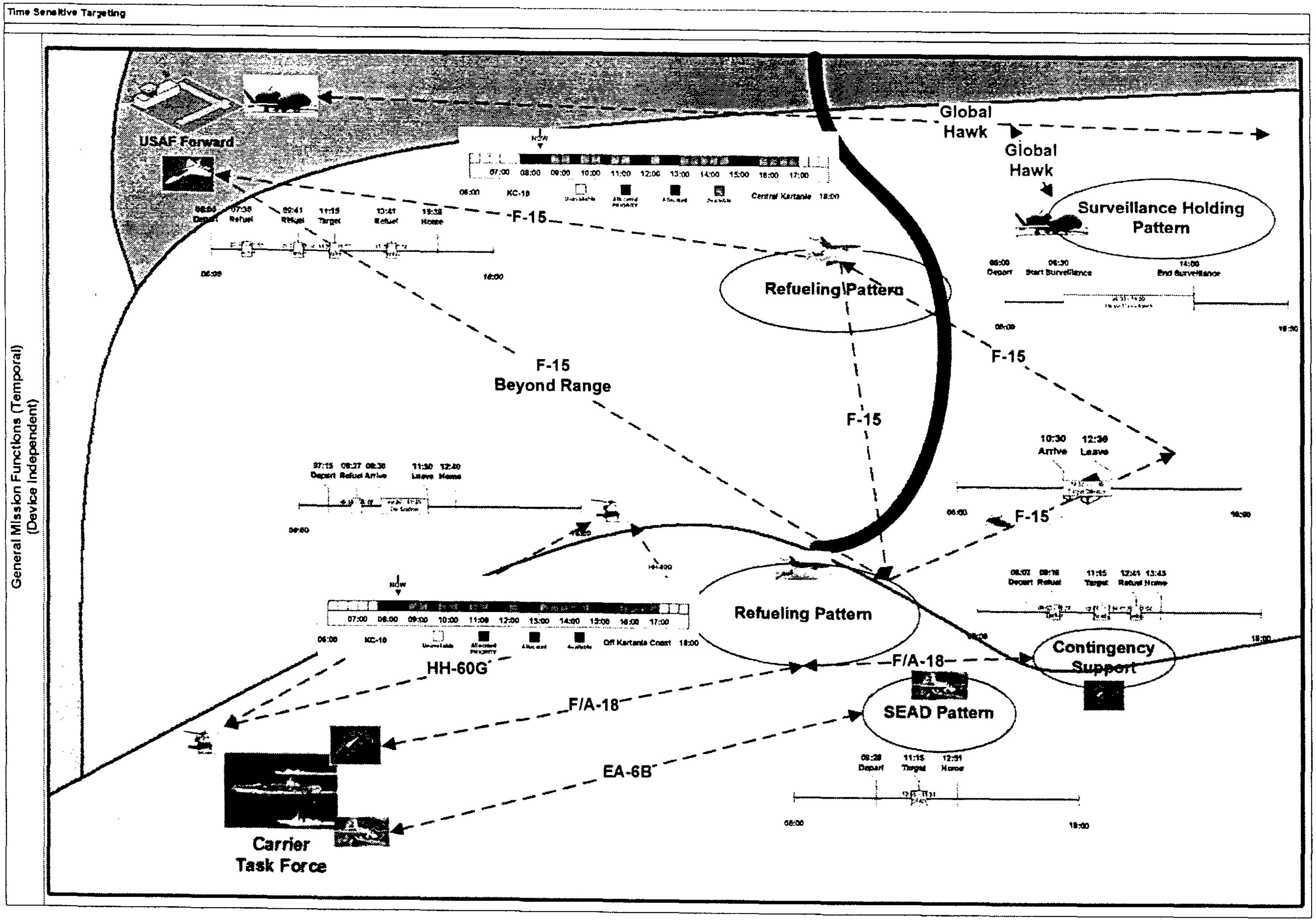

Figure 23: Timelines for various assets involved in the planned operation (see Figure 24 for legible versions of key elements)

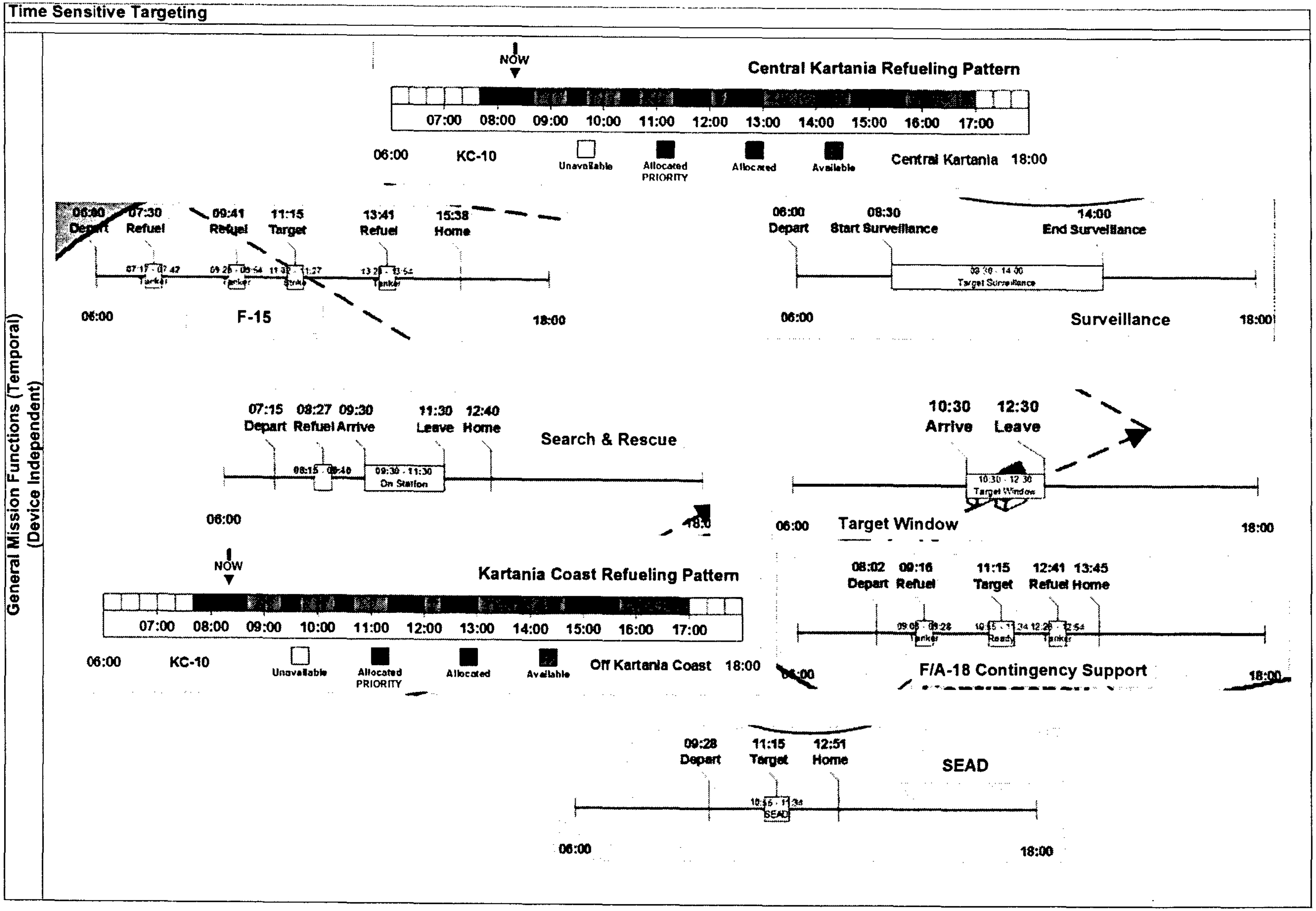

Figure 24: Key elements of Figure 23 magnified to readable size (in the approximate spatial relationship of Figure 23)

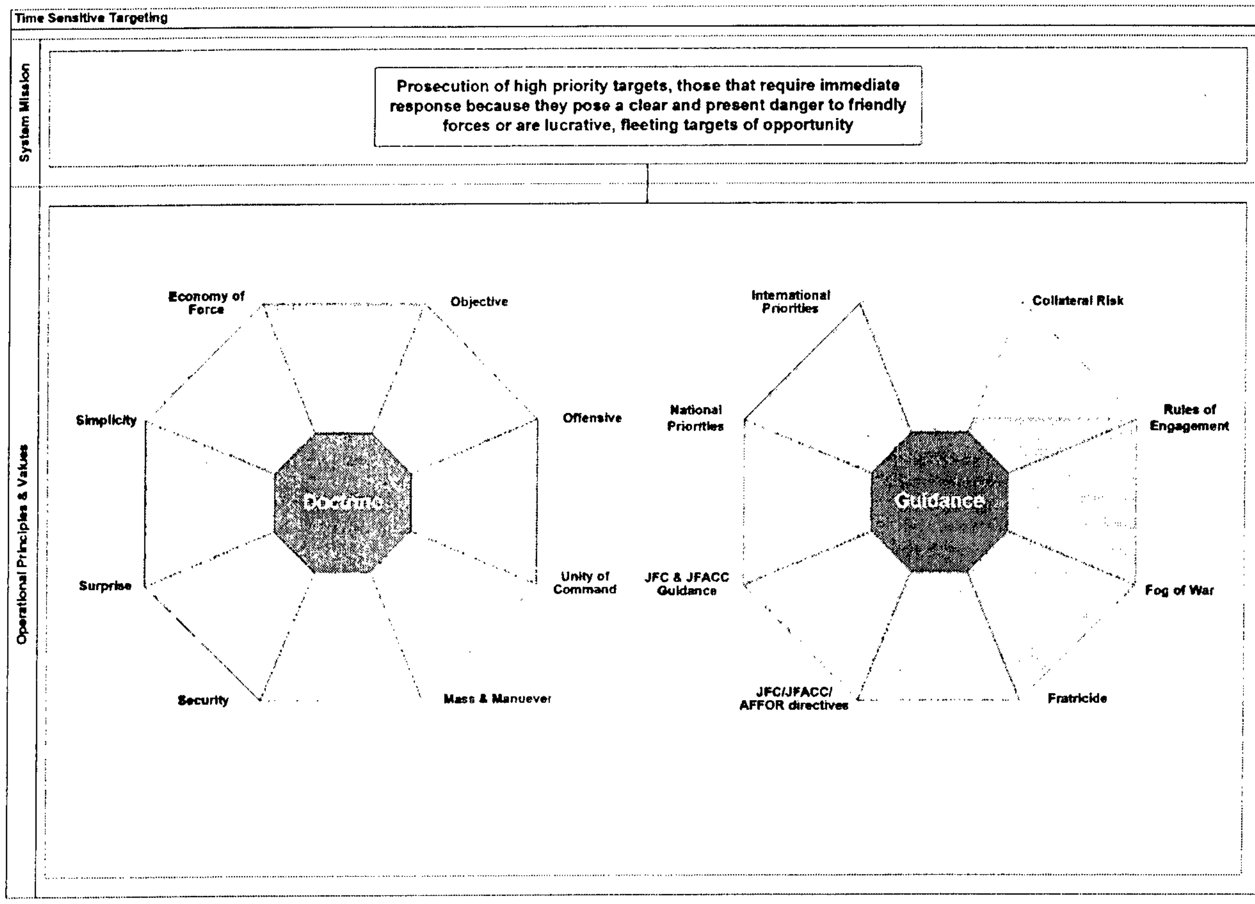

Figure 25: Purposes and Operational Principles & Values with a depiction that signifies a concern for issues surrounding collateral risk

Hand Off

Once the plan is verified, it will be handed off for execution. It may be posted to an electronic information system (currently the Automated Deep Operations Coordination System or ADOCS) and aircrew may be advised directly or via the Airborne Warning and Control System (AWACS). Ideally, all information—target coordinates in particular—will be transmitted electronically, but that is not necessarily possible in all cases. In the worst case, a targeteer from the Time Sensitive Targeting cell may have to relay coordinates to the AWACS by voice link and those coordinates may then have to again be relayed by voice link from the AWACS to the strike aircraft. In addition, if visual sighting of the target is required, the pilot may have to be talked onto the target by the AWACS controller relaying a series of identifiable landmarks to him or her in real time.

INFORMAL TEST

During the evolution of this Reasoning Space it seemed there would be some value in developing a minimal test case as shown in Figure 26. The left panel depicts a fragment of the reasoning space for air defense of the naval task force. The purpose of this subsystem is to coordinate defenses against a potential attack from the air. The right panel shows a potential trajectory through the reasoning space.[5] The potential trajectory first establishes the system purpose, which is to coordinate the air-to-air and surface-to-air defenses of the task force. There is a potential threat from the adversary's fighter assets and so the trajectory identifies those assets and then examines their threat potential. Given an understanding of that threat potential, the trajectory then identifies the defensive resources of the naval task force, first aircraft and their capabilities and then missiles and their capabilities. All capabilities are compared in terms of defensive coverage demand versus defensive capability and finally assessed in relation to the risk balance for task force protection that results from this configuration of assets.

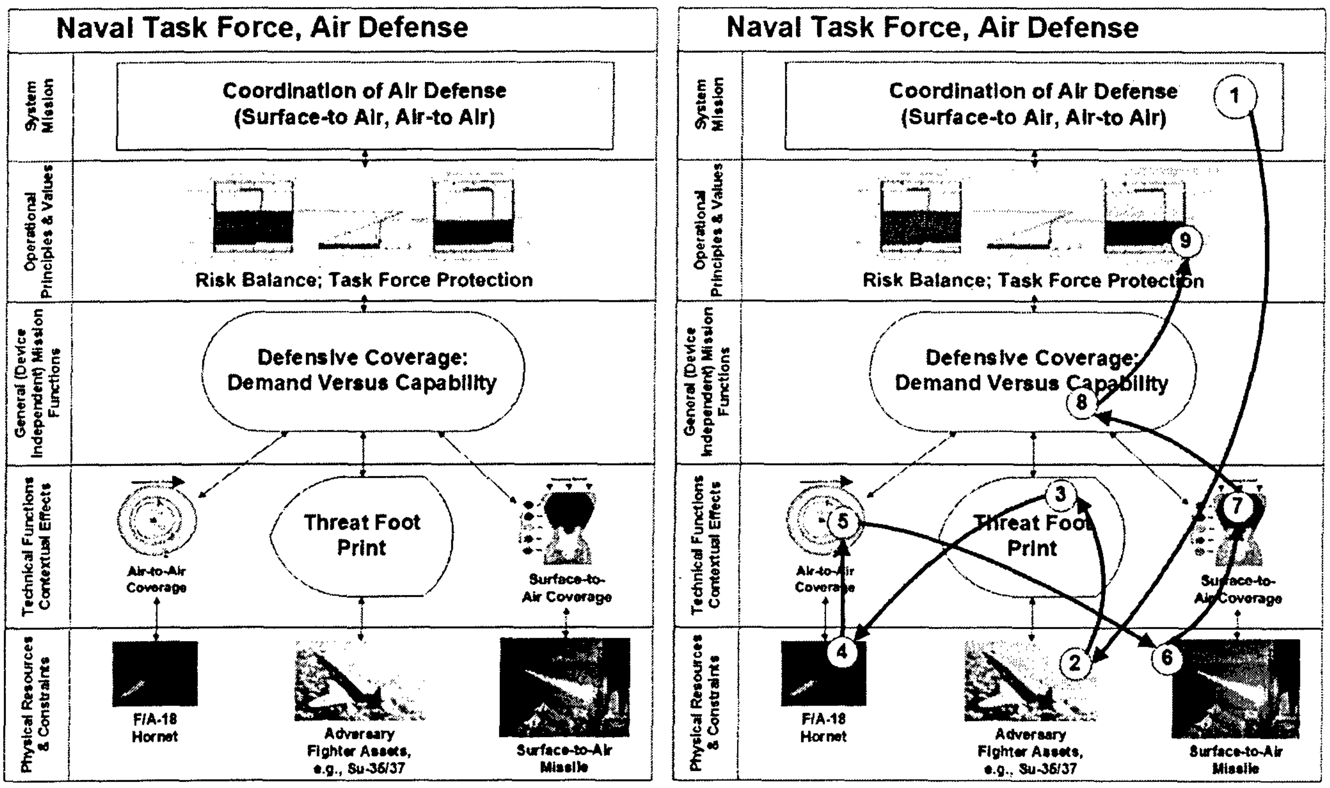

Figure 26: A fragment of the reasoning space for air defense of a naval task force (left panel) and a potential trajectory through that reasoning space (right panel)

[5] Note that this trajectory has been created as an illustration and it remains important to collect actual trajectories with individuals knowledgeable in the domain who have not been involved in the developments reported here. An actual evaluation that resulted in sensible trajectories would provide considerable support for the ideas outlined in this report.

RESOURCE DESCRIPTIONS VIA EMBEDDED HYPERLINKS

Earlier discussion referred to hyperlinks embedded in depictions of resources that would lead to a succinct and focused description of the resource. The documents I consulted in the development of this reasoning-space concept had a considerable amount of detail about specific resources that might be of general interest, but that impeded the review of information critical to mission planning because it was irrelevant to the targeting task. The embedded hyperlinks for a reasoning space should access a succinct but informative description of details relevant to the planning tasks to be supported by that space. Information not specifically relevant to the work supported by the reasoning space should be excluded, although some care must be taken in deciding what is relevant and what is not. Information should not be excluded merely because it is not relevant to a specific scenario. Different planning tasks will inevitably require access to different constellations of information, and the reasoning space should include all information that can be relevant to the full task range (i.e., the work). In addition, those documents should be consistently structured and formatted to support side-by-side comparisons between resources that permit different functional capabilities to be readily assessed.

Early in the development of the reasoning space, I conceptualized that description as a text document. Pop-up summaries of that type are shown for the F-15 Strike Eagle (Figure 27), the A-10/OA-10 Thunderbolt (Figure 28), the Global Hawk UAV (Figure 29), and the KC-135 and the KC-10 tanker aircraft (Figure 30). Note that the information content of these examples, abstracted from an unclassified web site (http://www.af.mil/factsheets/), remains incomplete. For example, three entries in the callout for KC-10 (Refueling time for each aircraft, Number of aircraft serviced concurrently, Maximum time on station) and two for the KC-135 are placeholders for information that is probably important but is not available from the documents consulted for this project.

Somewhat late in this project, it became evident that these pop-up summaries could be structured in the form of an Abstraction-Decomposition space. At this time, my thought is that the more detailed descriptions of specific resources should cover the bottom three levels of abstraction (Physical Resources & Constraints, Technical Functions & Contextual Effects, and General Mission Functions) and where possible, should contain graphics rather than text. Many of the graphics shown previously would be suitable (e.g., Figure 10 and Figure 17). This vision of how to represent a summary of the specific resources came to me too late in the project to develop it fully, but it offers one opportunity for further development.

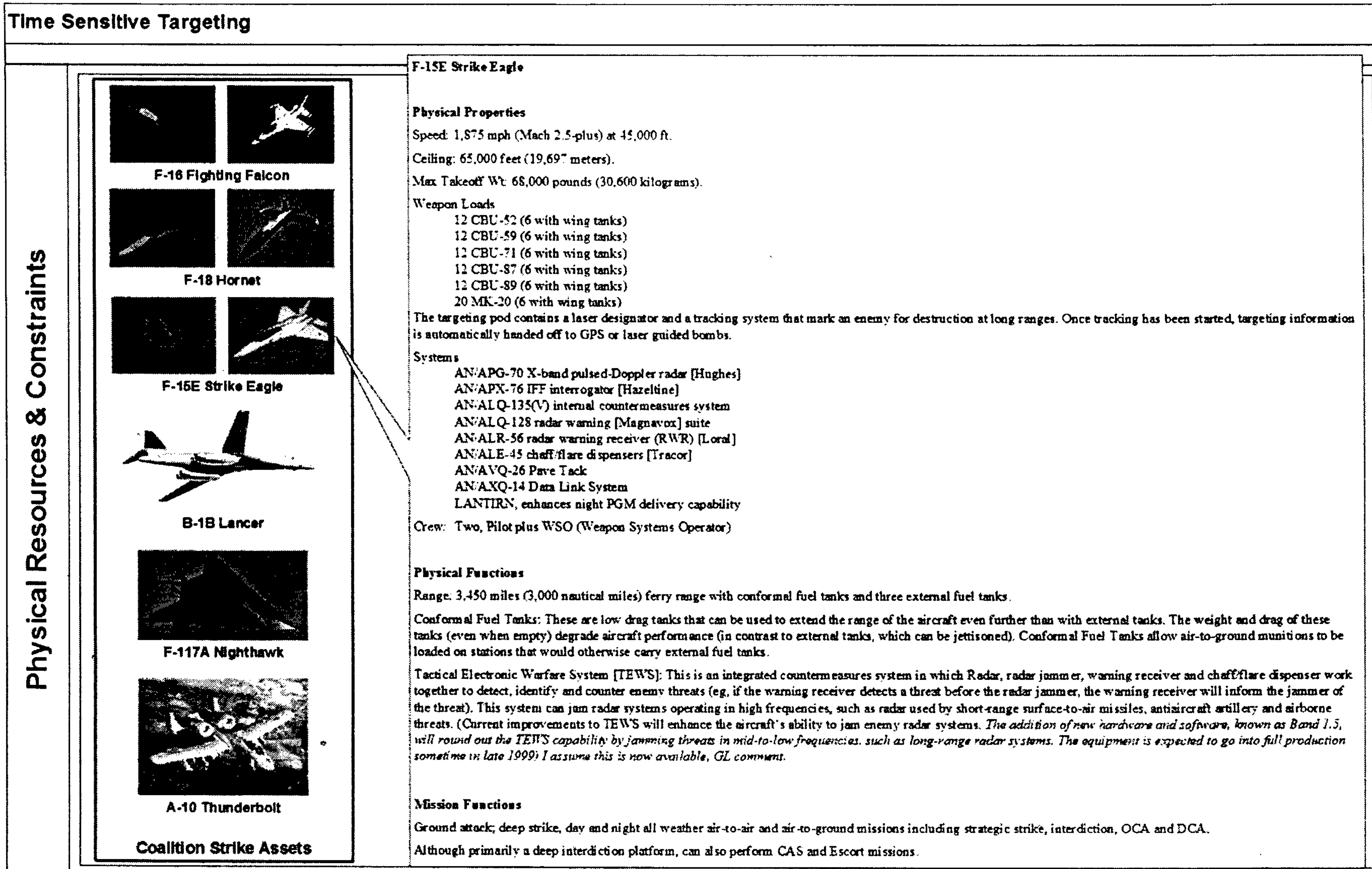

Figure 27: A hyperlinked summary (shown here as a pop up) of the F-15 Strike Eagle

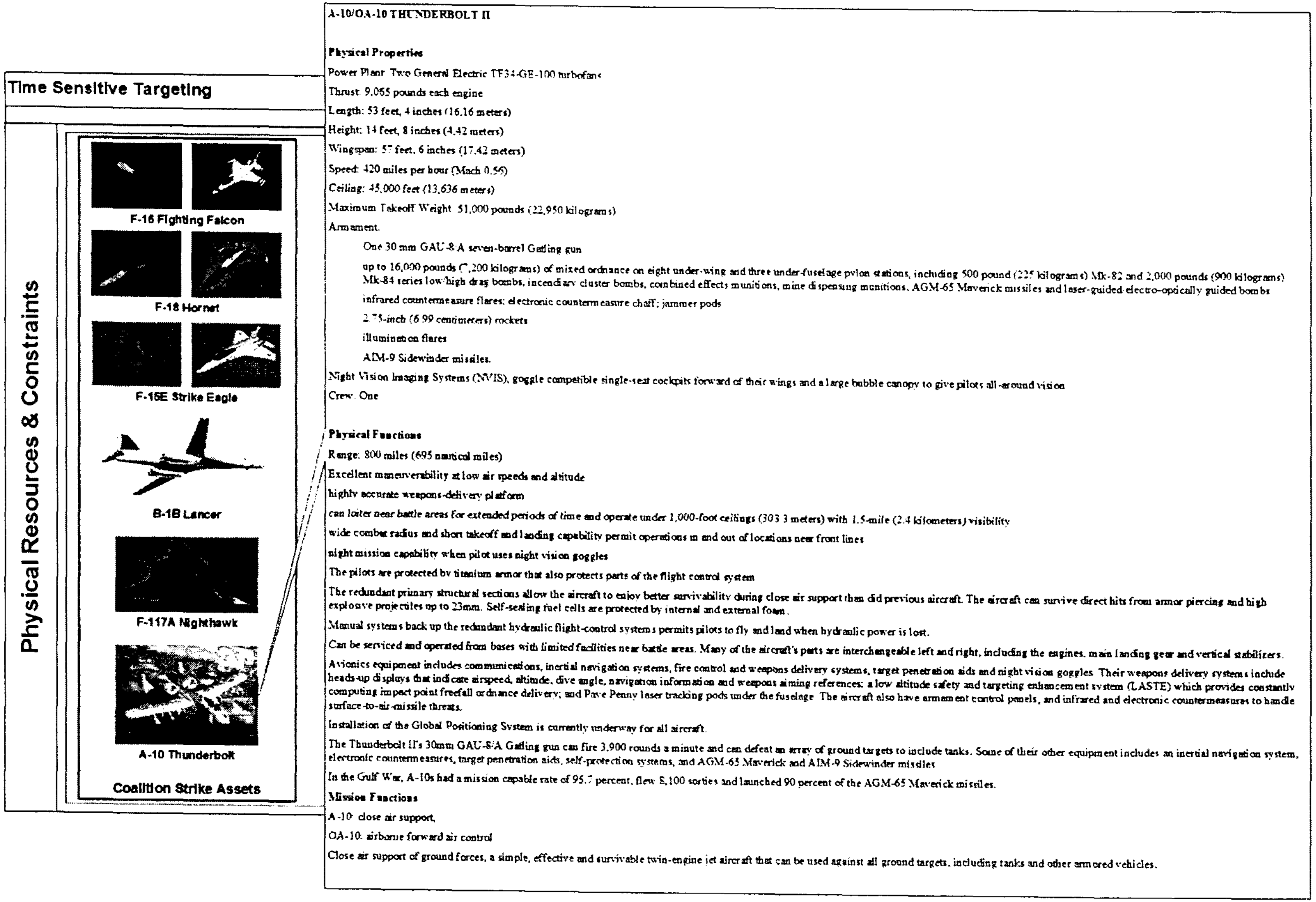

Figure 28: A hyperlinked summary (shown here as a pop up) of the A-10/OA-10 Thunderbolt

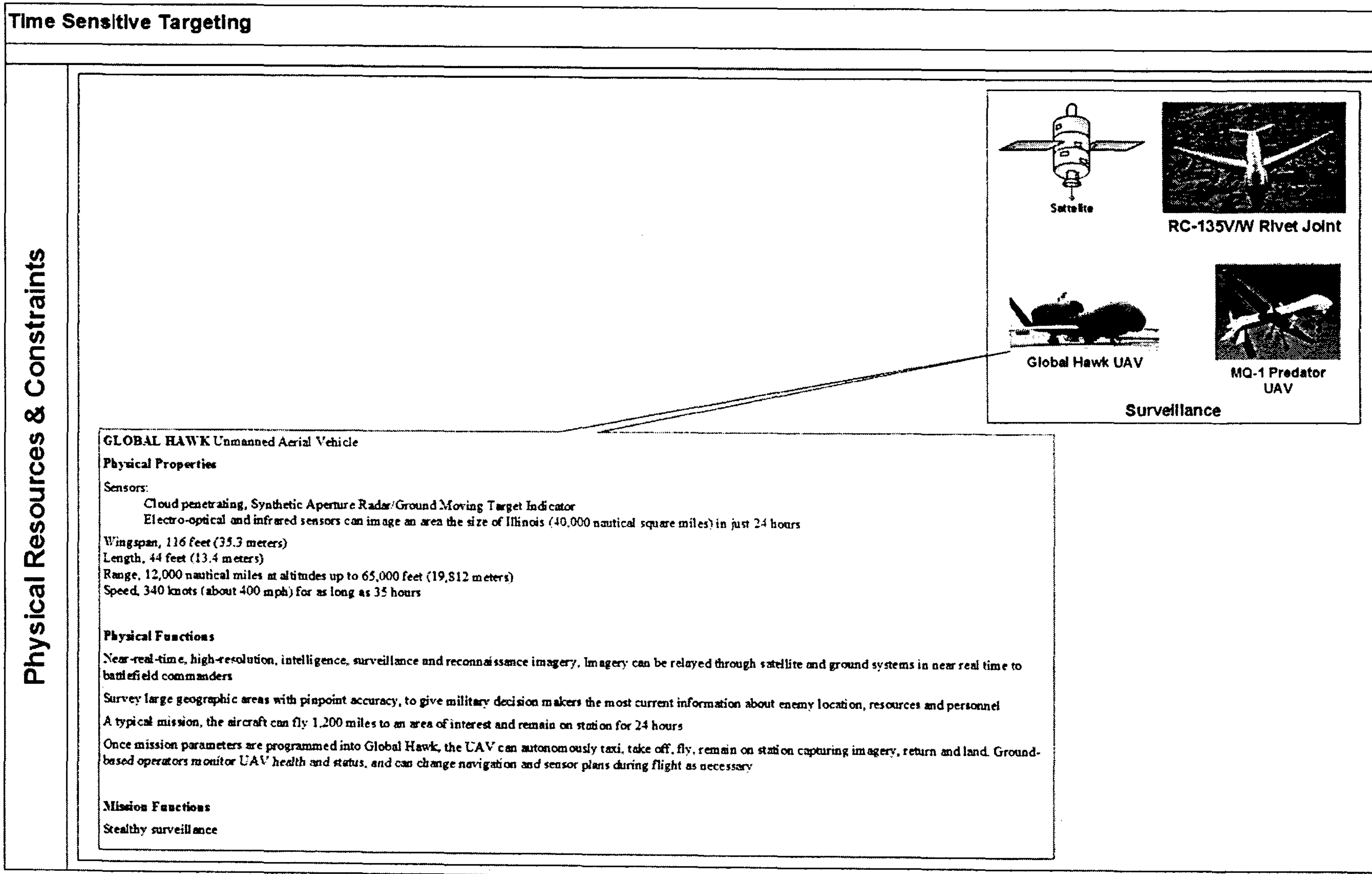

Figure 29: A hyperlinked summary (shown here as a pop up) of the Global Hawk UAV

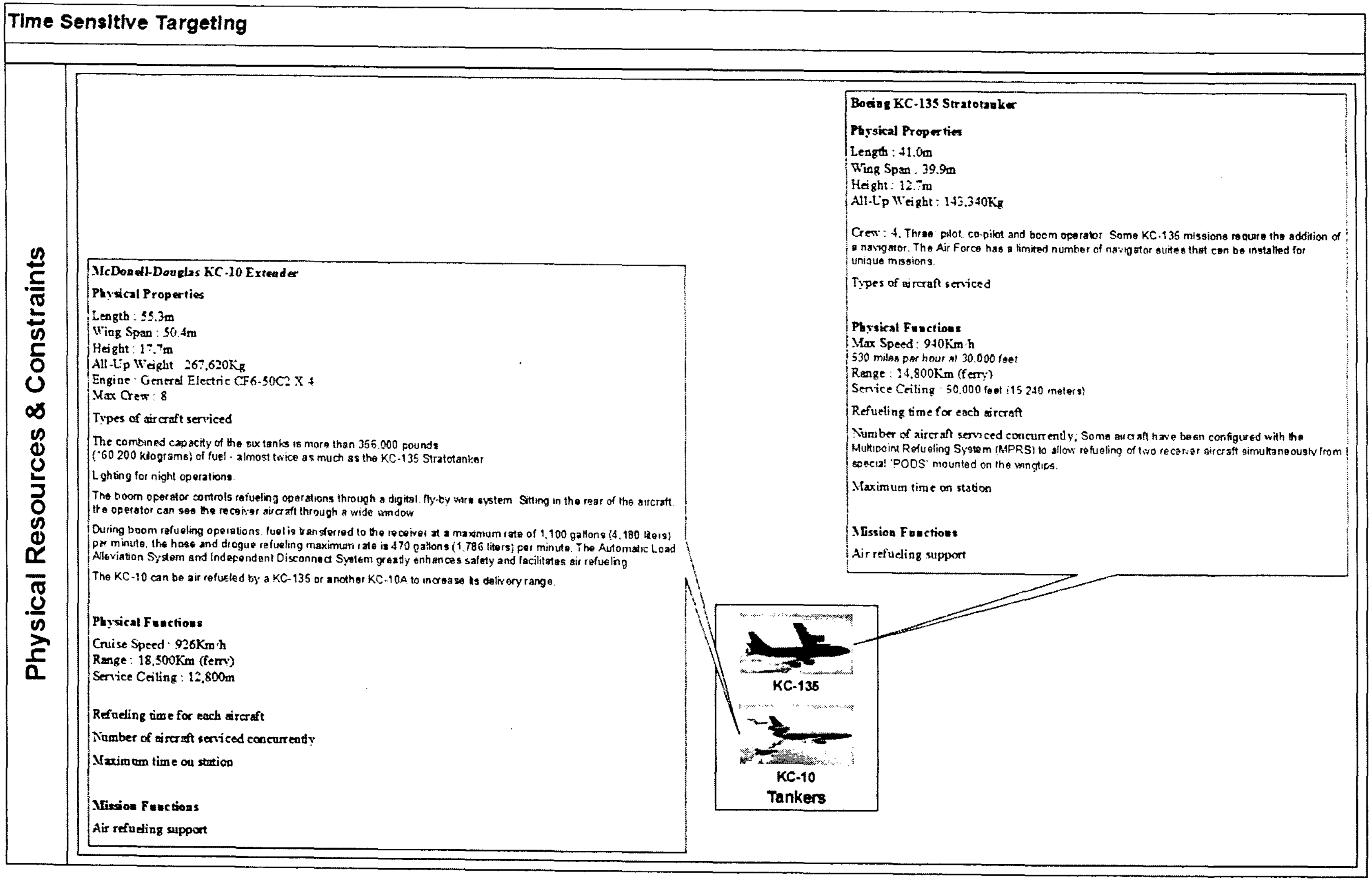

Figure 30: A hyperlinked summary (shown here as a pop up) of the KC-135 and the KC-10 tanker aircraft

SYSTEM SPECIFICATIONS

There is a requirement for this project to outline the specifications for the reasoning space that has been developed. It is common in technical design projects to write specifications in the form of a text document. For design of cognitive systems at least, that is an ungainly—and inevitably unsatisfactory—strategy. One of the forces that motivated this project was to find a better way of transmitting specifications. Consistent with Lintern (2005), this work assumes that engagement on representational forms will be much more effective than a text document in helping software engineers design and write code to satisfy the requirements.

It would negate the foundational philosophy behind this work to provide specifications for the reasoning space in the format most often used for specification of a technological product. Instead, the preferred strategy is to specify requirements via a storyboard narrative that demonstrates how the human agents will interact with each other and with the technological features of the system (Lintern, 2005). To that end, the use narratives provided above should be viewed not only as an illustration of how the reasoning space will be used, but also as a specification for how it should be implemented in software—albeit a partial specification as yet. It is not the proper role of cognitive engineer to advise a software engineer how to structure or write code, but rather to ensure that the software engineer understands the functional requirements. That is far better accomplished by an evocative storyboard than by a set of written instructions.

One dimension of specification not treated in the storyboard narrative relates to how the reasoning space might be implemented as a three-dimensional workspace. Although discussion of three dimensionality can evoke thoughts of holographic or binocular displays, it is thought at this time that perspective views represented on a flat panel screen will satisfy the requirement—although it is likely that a panel much larger than the typical size will be desirable. An electronic tabletop of the type depicted in Figure 31 may be required to allow a comprehensive overview of the total space of an extensive knowledge domain. Because of limited resources, the three-dimensional format has not been illustrated in this project. The reasoning space has instead been depicted as a series of two-dimensional panels—see Figure 5, (also Figure 25), Figure 8, Figure 9, and the set that depicts different views of General Mission Functions, Figure 21, Figure 22 and Figure 23.

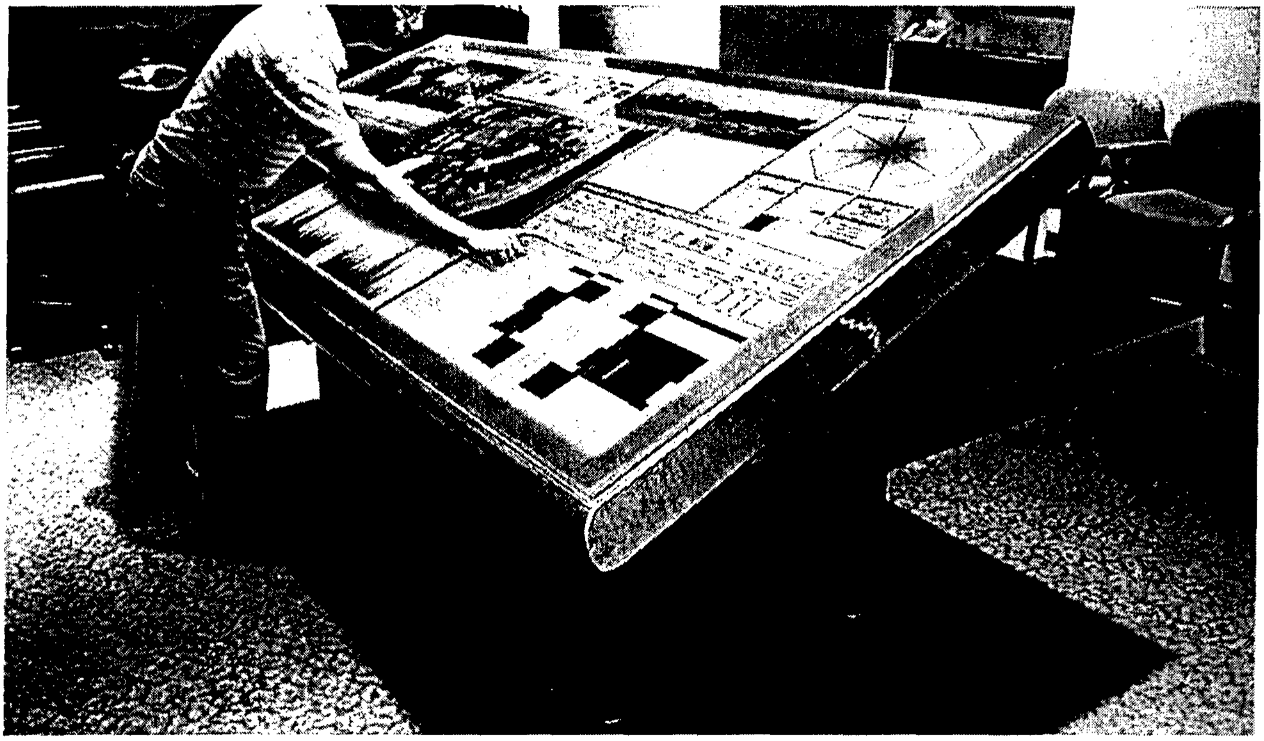

Figure 31: A depiction of an electronic table top that might be used to explore a full reasoning space for a complex socio-technical system

IMPLICATIONS OF THE REASONING SPACE FOR SYSTEM DESIGN

What is striking is the disconnect between operations as viewed at the top and operations as implemented on the front line.

Weick and Sutcliffe (2001), p 14

The reasoning space is not a design artifact in itself but a domain knowledge system. Its development is based on the assumption that those who know the functional structure of the system and the processes that operate within it will be better placed to design support systems for it or to redesign it. As Vicente (1999) argues, the complexity of a technological support must reflect the complexity of the work. This view is consistent with the Law of Requisite Variety (*only variety can destroy variety*, Ashby, 1957, p207), here taken to mean that only variety can control variety. In other words, the controller must have as much variety as the system it controls [http://artsandscience.concordia.ca/edtech/ETEC606/requisite.html]; the functional scope and granularity of a workspace must match the operational complexity of the work. While Ashby supported his law with a rigorous mathematical analysis, it also makes intuitive sense; a system that has more behavioral options than its controller always has the potential to surprise or outmaneuver its controller.

The central problem to be addressed by use of the reasoning space is resolution of the disparity between design conceptualization and the natural strategies available to operational personnel. Typically, those who design major systems fail to appreciate the subtle complexities of the work. Within the socio-technical design world, there is what Weick and Sutcliffe (2001) refer to as "mindlessness." Their discussion is specifically about the conceptual disengagement of management from operations. They argue that a socio-technical system needs a common language that is understood at all levels; a language that can be used to understand operational complexity. In management, the problem surfaces through disparity between management and operational staff in understanding what it means to be sensitive to operations. For management operational issues relate to organizational structures and financial accountability, while for operational staff they relate to issues surrounding execution of the work.

In design of socio-technical systems, there is a similar disparity. Designers are concerned with developing a technical system that works, while operational personnel are concerned with how these tools support their work activities. In principle, there is no need for these two perspectives to be at odds, but for there to be an effective synergy designers need to understand how their system integrates with the complexity of the work. Designers typically have an impoverished view of the nature of the work, and the technological work supports they develop reflect that view. The preceding discussion has outlined how a designer might proceed to become familiar with the operational complexities of the work (its functional scope and granularity) as a means of developing a more realistic (Weick and Sutcliffe use the term, "more mindful") appreciation of operational activities. To supplement that discussion, this section of the report illustrates how that operational knowledge can guide system redesign.

Three examples are outlined below to illustrate how use of the reasoning space might help a design team envision an innovative work support and then lead that design effort in a productive direction. The examples chosen for that illustration emphasize applications from the domain of cognitive engineering, but the reasoning space is intended to be more general than that and should be useful for designers from other technical disciplines. Cognitive engineering examples have been selected for illustration primarily because I, as a cognitive engineer, could not develop credible illustrations that emphasize the contributions of other disciplines. It would nevertheless be valuable in further development of this reasoning space to engage members of other technical disciplines to assess whether their work would also benefit.

In the review of these illustrations, it should be noted that the reasoning space is about specifics of a work domain and that no design effort can proceed only on that basis. A designer brings experience and knowledge about general principles, and any successful design effort will combine that sort of knowledge with specific knowledge about the work domain. In addition, it should be recognized that there are certain creative elements in the process of design that defy logical or explicit description. The best that can be said is that creative innovation emerges through an abductive leap. Creative design is not, as some seem to imply, a combinatorial search through a high-dimensional state space. Instead, innovation builds on extensive knowledge of and familiarity with the design space through a process in which designers become aware of new possibilities via what can be best described as insight.

Team Design

Our primary recommendation was to reduce the number of people in the technical support center. The excessive staffing produced confusion about roles and functions and led to the "social loafing" phenomenon in which team members come to define their roles more narrowly and to assume that others will handle new tasks.

Klinger & Klein, 1999, p 23

Lean manning has become an important design goal for many military systems. The problem is generally seen as one of the combining work roles without inducing cognitive overload, and automation is promoted as the primary technological solution. This strategy does not, however, offer anything useful for the concept refinement phase of systems acquisition. A strategy based on the global functional requirements would be a more effective approach.

The recommended strategy, motivated in part by work that has shown increased efficiency of teamwork with well designed reductions in manning (Klinger and Klein, 1999), is to first establish an efficient global functional structure and to then descend through organizational layers, defining functional structures in terms of functionally oriented organizational units, until work is allocated to specific agents, either human or technological. To ensure that the illustration outlined here is concrete, the existing functional structure of the Air Operations Center, as shown in Figure 32, is accepted. Time Sensitive Targeting, as discussed earlier in this report, is identified more generically as a real-time planning and targeting function. It is located in the Offensive Operations unit within the Combat Operations Division.

The design goal is to establish viable work packages, where a work package is defined as that constellation of work products that can be delivered by one human agent with the support of any assistive technological functions that can be provided. In any complex socio-technical system, work packages will be interdependent but they should be designed as far as possible to be modular in the sense that their reliance on other system products should be minimized. Communication overhead offers possibly the best illustration of this principle. It is well known that communication between agents places a load on the system. Where at least one of those agents is human, the requirement for communication increases coordinative challenges and cognitive load. Efficiencies will be realized when the complexity and frequency of communications undertaken by human agents are minimized.

By developing a plan within the reasoning space, a human-systems designer or analyst will gain an idea of what type of work is involved, and how time consuming and cognitively intensive it is. For the narrative in the section titled **A Planning Trajectory for a Human-Systems Designer**, a single person does the planning and then passes the plan to the cell chief for review. In practice, there are at least three members of a Time Sensitive Targeting cell to do this work, a targeteer, a rerole officer, and an attack coordinator (Lintern, 2005). The human-systems designer or analyst could use his or her planning experience gained in working through the reasoning space to consider how a plan in development is handed from one member to another, and could consider whether a different configuration of the work is desirable.

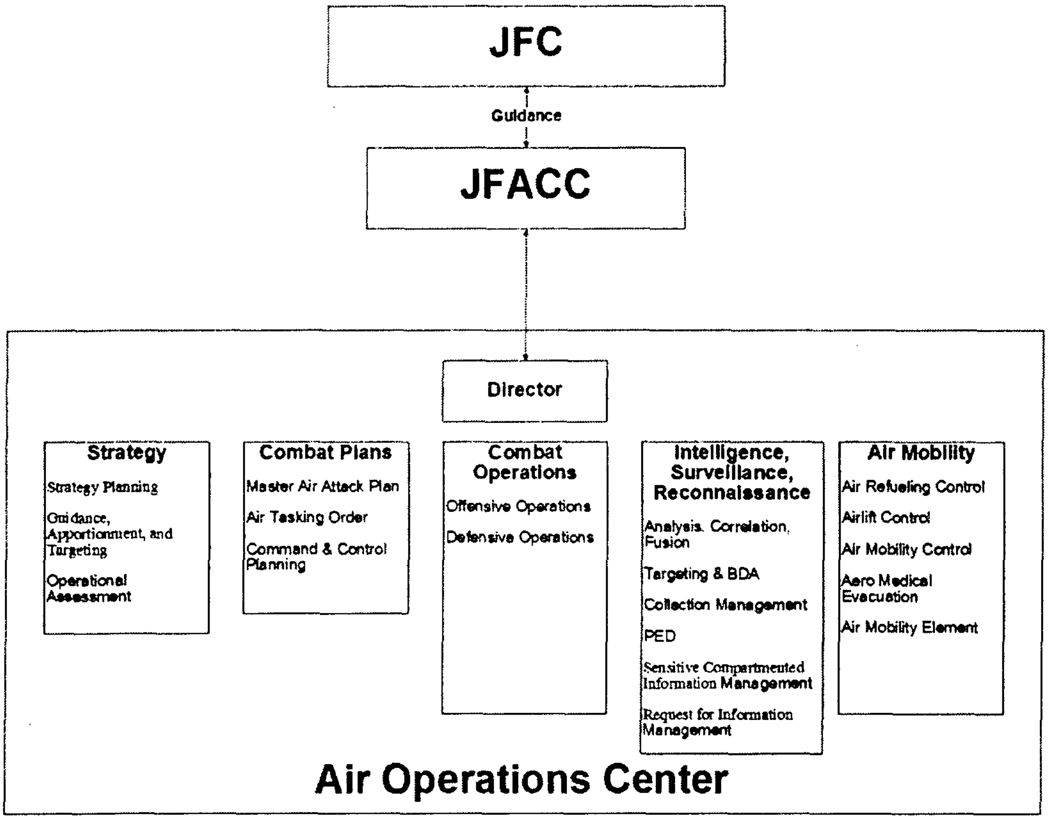

Figure 32: Functional organization of the Air Operations center

The illustration of Figure 33 suggests an organizational concept for real-time planning and targeting. A human-systems designer or analyst who has studied the reasoning space and worked through narratives would now understand what tasks have to be accomplished within the process of real-time planning and targeting. By working through the scenario narratives in particular, he or she would have come to understand the linkages between the various subtasks. It should be possible at this stage to propose how the total work package might be modularized.[6] Two or three different structures might seem possible.

There is often a time constraint on developing a plan. The human-systems designer or analyst could use the reasoning space to consider whether current and alternative configurations can result in the plan being finished within that constraint. In a previous project, one subject matter expert spoke of an arrangement in which the duties of the targeteer and the rerole officer were combined in a manner that permitted more efficient planning, and also permitted planning for two targets simultaneously. The designer might use the reasoning space to work through the planning process under each of these configurations, possibly with the collaborative assistance of a subject matter expert much as has been done by Naikar, Pearce, Drumm and Sanderson (2003)

[6] Note that the possibilities for redesign emerge via abductive reasoning, otherwise known as insight. The role of the reasoning space in this process is to help the designer become sufficiently knowledgeable that the insights reflect the complexity of the work.

with tabletop analysis in their work on team design for the Australian airborne early warning system. This process will help the human-systems designer or analyst think about different ways of configuring the planning team and of providing suitable collaborative support.

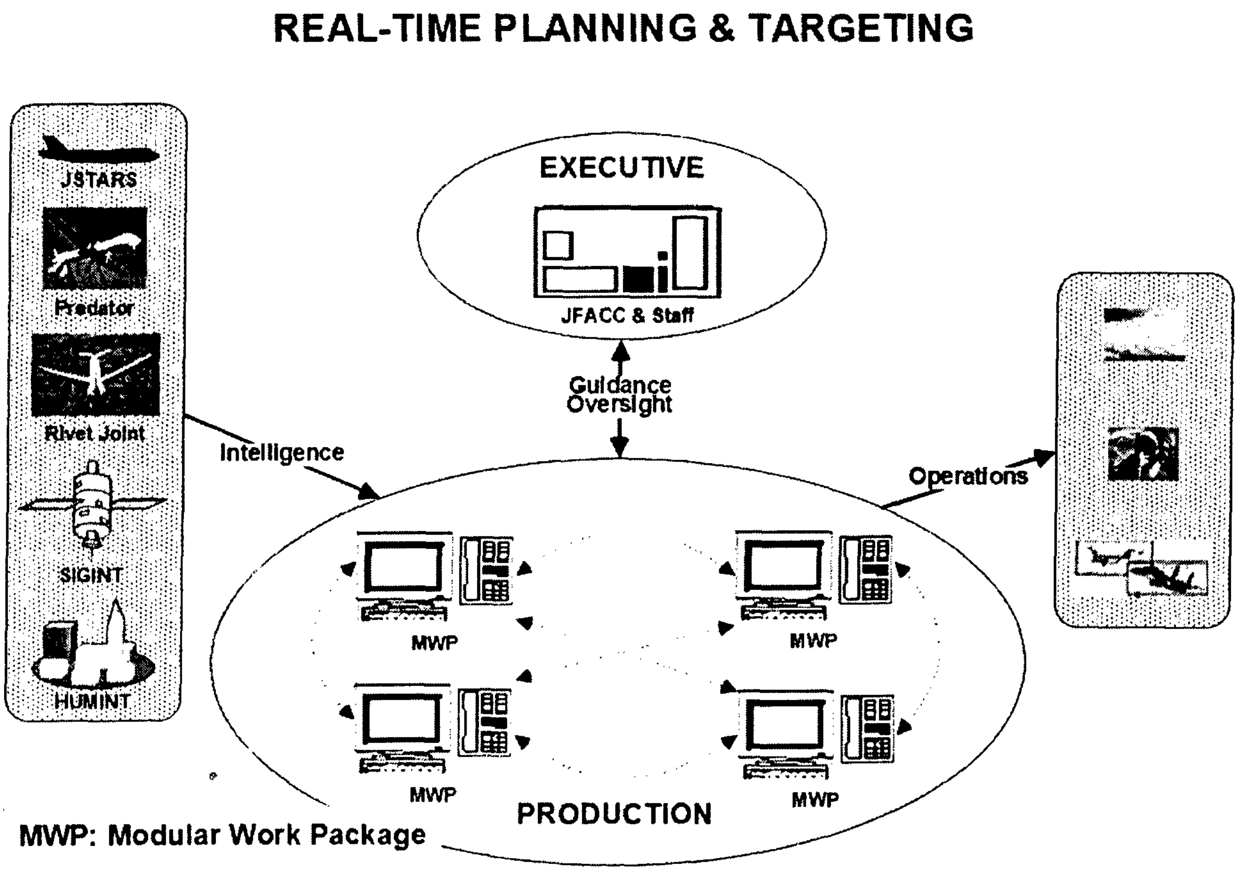

Figure 33: A modular work package (MWP) scheme for real-time planning and targeting

Workstation visualization

Many of the depictions in the reasoning space described here could potentially provide effective visualizations within an actual Time Sensitive Targeting cell. For example, an integrated depiction of the target area, as shown in Figure 4, may enhance the sensitivity of the planner to the collateral damage constraints, the problems associated with enemy ground offenses, and features that may be used to help the attack pilot locate the target. A formal workspace as developed by Lintern (2006) for counterinsurgency planning could possibly be developed, and much of what has been shown in Figure 5 through Figure 25 could be useful for that workspace. These ideas would constitute design hypotheses about what might be useful, and the designer (after first laying them out in some configuration) could explore their value by working through scenario narratives within the reasoning space with the assistance of one or more subject matter experts who would most likely suggest variations and extensions.

Large-Screen Wall Displays for an Air Operations Planning Center

There has been relatively little thought about what sort of content the large-screen wall displays in an Air Operations planning center should contain. Following Clark's views on ubiquitous computing (Clark, 2003), I suggest that common wall displays should provide contextual and structural information (for maintenance of global situation awareness) that operational staff would assimilate with little conscious effort. That information should not, however, capture attention. In a previous project (Lintern, 2005) a subject matter expert stated that the large screen display of an Air Operations planning center in which he worked carried a continuous feed from a commercial 24-hour news channel. Many on the operational floor would watch that and, in particular, video of weapons strikes captured the attention of many. In a similar vein, direct feeds from unmanned air vehicles or from strike aircraft might be popular.

Popularity is not the essential aim. While observations of subject matter experts are valuable, they should not be permitted to enslave design.[7] Ideally, large-screen wall displays will offer information that provides context for the more focused information that can be accessed through an individual workstation for a specific planning task. Hypotheses about what constitutes contextual information and would be of general use as ubiquitous or orienting information can be identified by examination of resources and constraints as shown in Figure 8.

Any information selected for wall screen presentation should be presented pictorially for tacit assimilation. A display of current or anticipated weather patterns throughout the area of operations, a display of the area of operations with key features highlighted, or a display of ongoing air and surface missions (as in the old-style sand table) may be useful. The general patterns would provide context for any specific planning task and would support situation awareness. Where more specific details are required, a particular staff member could access those through his or her own workstation.

SUMMARY

The development of the reasoning space and the discussion above have been motivated by the view that the most serious impediment to the effective design of a complex, socio-technical system like an Air Operations Center is the difficulty of developing innovative ideas that address important work constraints as that work unfolds in actual operations—rather than as it is envisaged from the relative safety, comfort, and organization of a high technology design environment. The primary purpose of the reasoning space is to bring into that high technology design environment an appreciation of the complex demands and the operational constraints that interact to generate an often-confusing work environment that cannot be understood in depth or at any meaningful level in the abstract.

Lintern (2005) has promoted the development of a rapid prototyping tool that would enable a multidisciplinary design team to explore the implications of various cognitive specifications and evaluate various system configurations. Design is viewed as a creative dialog among members

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[7] One can imagine that commercial films would be popular but they would not support the work at hand and would serve primarily as a distraction.

of a design team with different areas of expertise. The reasoning space discussed in this report offers a means for an individual designer to develop a personal dialog, and to then share it and extend it in interaction with others as they also work collaboratively through the reasoning space.

The purpose of the reasoning space is to help a design team identify areas of work where some form of work support may assist the workflow. The knowledge acquired from the space should then help the design team conceptualize a work support that would be effective. Within a socio-technical environment in which operational personnel discard many new support systems because they are too cumbersome or too poorly conceptualized, effective use of the reasoning space in this manner could constitute a huge advance. Whether the reasoning space can, in fact, be effective in these terms can only be confirmed in use; designers must use it to develop work supports and then those work supports must find favor with operational staff and result in improved workflow for them.

As noted earlier in this report, Cognitive Systems Engineering is an analysis and design discipline for Human-System Integration within socio-technical systems. Analytic methods focus on the complexities of work by identifying why the work is cognitively difficult, the types and levels of expertise required, the functional or informational structure of the work domain, the tasks or processes employed, the means by which workers develop situation awareness, and the means by which workers coordinate and communicate. A deep understanding of the work domain, as facilitated through use of the reasoning space, should help a designer formulate solutions to such issues.

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APPENDIX A. A WORK DOMAIN ANALYSIS TUTORIAL

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BACKGROUND

This tutorial was developed by Dr. Gavan Lintern. Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defense Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering.

INTRODUCTION

Work Domain Analysis identifies the functional structure of a socio-technical system. That functional structure will encompass properties ranging from object descriptions, through specific and general functions, to values and specifications of system purpose. It will encompass functional properties that result from design intent but in addition, functional properties that may not have been intended but instead were discovered by operators, and both desirable and undesirable functional properties generated because of interaction with context or environment.

Work Domain Analysis identifies structure independently of activity. It can be likened to a map that lays out the structure of a geographic environment. Activity is important, but neither a Work Domain Analysis nor a map addresses that. However, both provide important leverage into planning of activity by laying out the resources available for action and the constraints on action. (Work Domain Analysis is part of a larger analytic framework, Cognitive Work Analysis, in which the later stages that reference the product of Work Domain Analysis deal with activity).

The approach might be clarified by consideration of the meaning of the terms *function* and *process*. These are troubling terms in engineering and science because their range of usage is broad and they have overlapping meanings. Within Cognitive Work Analysis, Vicente (1999) has given them constrained meanings that map onto the needs of this analytic framework. A *function* is a structural property of the work domain. A *process* is a mechanism by which the behavior of the system is produced. This distinction is unusual and no other strategy of cognitive analysis makes it explicit.[8] An underlying assumption of Cognitive Work Analysis is that the separation of structure from activity helps bring an important source of order to the analysis of complex, socio-technical systems.

The product of Work Domain Analysis is an Abstraction-Decomposition map; a two-dimensional matrix that distributes functions across levels of abstraction (object descriptions, physical functions, purpose related functions, values and system purposes) and across degrees of decomposition. By convention, abstraction is represented on the vertical dimension and decomposition on the horizontal dimension.

A major contribution of Work Domain Analysis is that it identifies means-end relationships between functions at different levels of abstraction. A means-end relation reveals the functions

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[8] Even within Systems Engineering, where this sort of distinction would seem to offer an advantage, Functional Analysis as discussed in many texts and reports (e.g., as in Blanchard and Fabrycky, 1990) is a functional flow analysis, essentially a process analysis.

at one level that must be used for satisfaction of a function at a higher level. In most cases, a constellation of functions at the lower level will be required to satisfy any function at a higher level.

In this discussion of means-end relations, the reference is specifically to resources that will be used to satisfy a functional requirement. It is often said that means-end relations describes *how* a function is achieved but the word *how* implies a reference to both resources and activity. In principle, a means-end relation could specify either and it could even be useful to have means-end relations specify both. However, the standard approach to Work Domain Analysis specifically excludes any form of reference to activity and so a means-end relation refers only to the resources that must be used to achieve ends (which is actually consistent with the accepted definition of a means test). You should note this carefully because it is a source of considerable confusion within discussions about Work Domain Analysis.

The remainder of this brief tutorial will focus on the Abstraction-Decomposition map; descriptions of how it should look and hints about how to construct it. Note however, that the construction of an Abstraction-Decomposition map requires considerable knowledge about the system under consideration. The assembly of that knowledge constitutes a major Knowledge Acquisition effort, typically an extraction of relevant details from document reviews and discussions with subject matter experts. There is little in this tutorial that tells you how to do that but if you need further advice on that aspect of Work Domain Analysis, I can suggest sources.

THE ABSTRACTION-DECOMPOSITION MAP

The concept of abstraction is depicted in Figure A-1. In this example, comfort is the most abstract function and is enabled by heating (a physical function) which is enabled by the furnace (a physical object). An important aspect not depicted in Figure A-1 is that both comfort and heating could be enabled by other sorts of resources not depicted here. The same abstraction shown in Figure A-1 is extended in Figure A-2 to depict decompositions that might be useful for the analysis of a heating system.

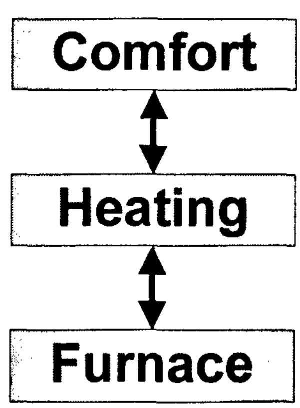

Figure A-1. A simple depiction of an abstraction relationship with means-end links shown

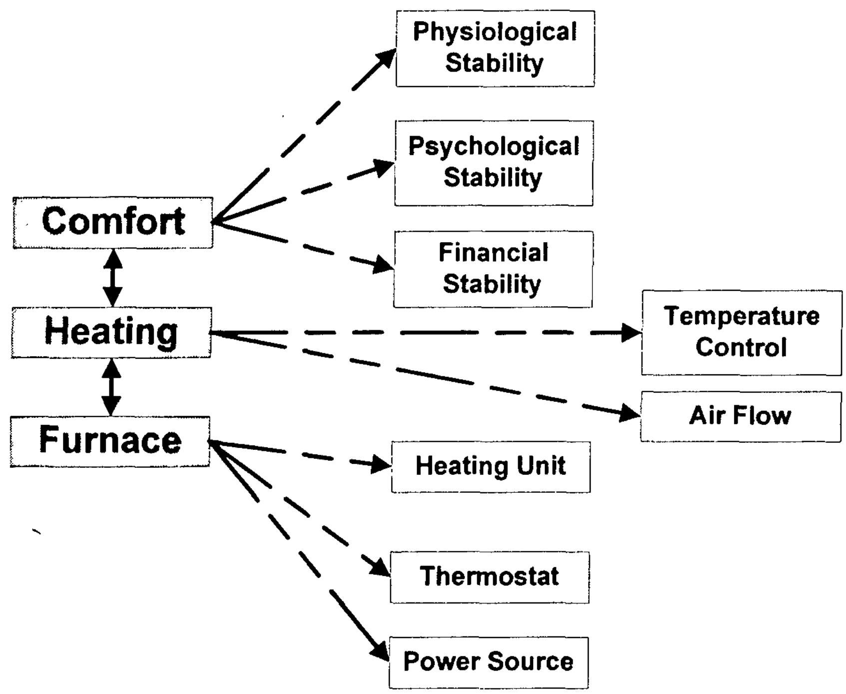

Figure A-2. A simple depiction of decomposition relationships, building on the abstraction of Figure A-1

The knowledge representation for Work Domain Analysis, the Abstraction-Decomposition map, provides the foundation for the design of a radically new system form. This map represents functional properties of the work domain (objects, resources, constraints, purposes) in a two-dimensional matrix (Figure A-3). Each node represents a function. The vertical dimension represents the dimension of abstraction and the horizontal dimension shows varying levels of decomposition (system, unit, component, part).

The abstraction dimension of an Abstraction-Decomposition map is typically organized (proceeding from top to bottom) through the hierarchy of:

- The **System Purpose;** the particular purpose that is the focus of analysis
- **Values and Priorities, Abstract Functions, Balances;** functions that encapsulate human and social values (e.g., safety-productivity tradeoffs, concerns about collateral damage, conservation concerns with regard to own personnel and resources) and thereby constrain the space of acceptable action
- **Purpose-Related Functions;** the general functions that will satisfy the system purpose
- **Physical Functions and Physical Effects;** the effects or processes supported by or generated by physical systems or objects
- **Physical Properties;** the physical properties of objects and devices such as location, layout, appearance and shape

Further discussion of the meaning of these labels to the levels of abstraction and tips for constructing an Abstraction-Decomposition map are presented in Appendix B of this report.

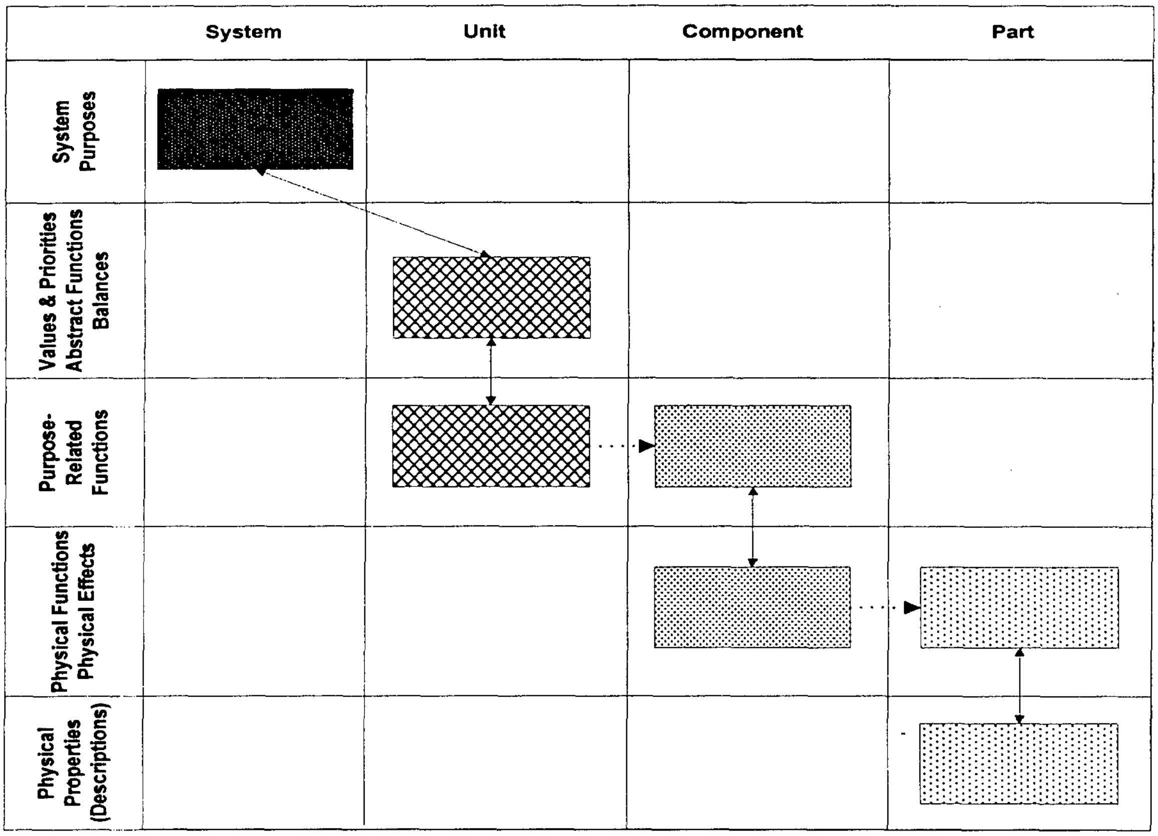

Figure A-3. The standard two-dimensional format of an Abstraction-Decomposition map

Abstraction levels are connected by means-end links, shown in Figure A-3 as solid, two-headed arrows. This form is used to indicate the reciprocity between related functions at different levels; a function is enabled or supported by functions to which it is connected at lower levels (its means) and conversely, a function is implemented to support or enable functions to which it is connected at higher levels (its ends). Decompositions within levels are represented by single-headed, dashed arrows with the arrow pointing in the direction of the decomposition.

You might need to deviate from the standard representational form for the Abstraction-Decomposition map because the multiple-column format cannot easily be made legible in a normal-size document page. An alternate form, shown in Figure A-4 relies on dashed arrows to indicate decompositions within abstraction levels and conversely, enclosures to indicate aggregations. A decomposition of system into units is shown at the abstraction level of Purpose-Related Functions and a decomposition of a unit into components and an aggregation of components into unit are shown at the abstraction level of Physical Functions and Physical Effects (at this level, the term *function* is reserved for the consequences of engineered artifacts while the term *effect* is used to refer to the consequences of natural phenomena such as weather). Decompositions should continue to the level of operational relevance.

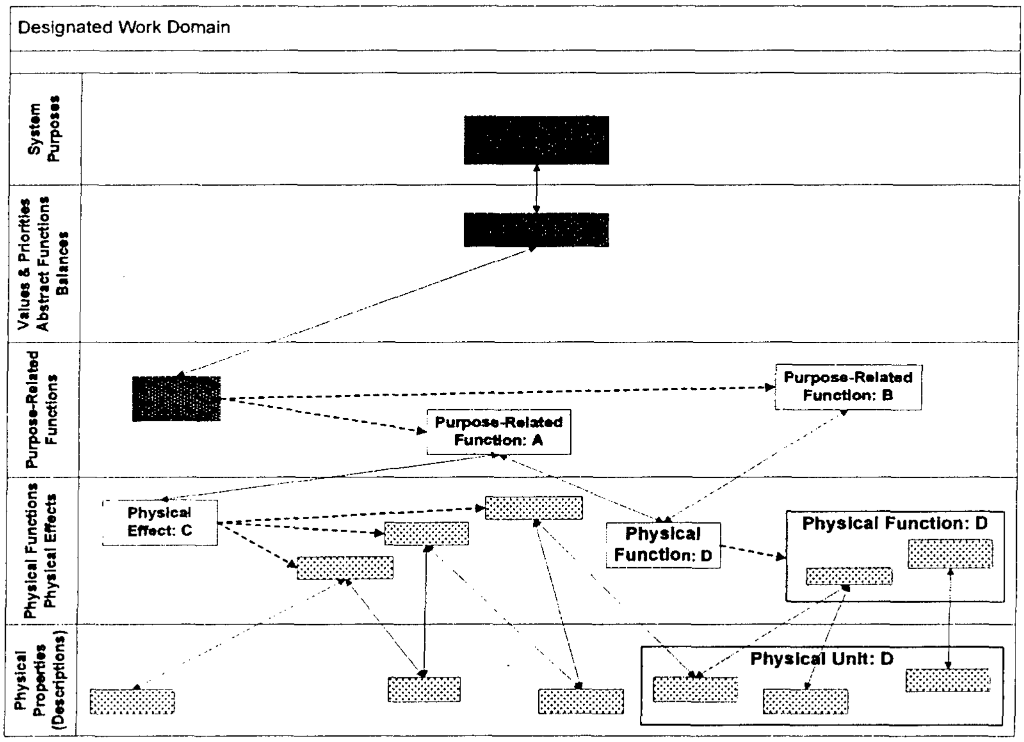

Figure A-4. An alternate format for an Abstraction-Decomposition map

Figure A-5 offers a tutorial example of an Abstraction-Decomposition map that shows some of the functional elements for home heating that contribute to comfort and health. Several features should be noted:

- The different types of function terms at each level.
- The means-end relations (two-headed arrows between levels)
    - The reason for a function at one level is shown by its connection to one or more functions at the next highest level.
    - The structural means of satisfying a functional requirement are shown by the means-end links to functions at the next lowest level
- Decompositions shown by dashed, single-headed arrows within levels.
- Interdependencies shown by the crossings of the means-end relations. Links from passive objects (insulation, enclosures) to heat extraction suggest interdependency, which here is that poor passive systems will exacerbate the load on the active system and will possibly cause an overload of the system.
- The means-end link from the passive to the active leg goes to the Heat Extraction process and not to the overload circuit. This is an important feature. We want to pose the issue at a general level. Cooling can be accomplished by different means (evaporative coolers are effective in low humidity environments would be terrible where humidity is high).
- The heat extraction process might overload because of poor insulation. Do you correct this problem with a higher capacity cooling system or better insulation? Work Domain Analysis does not answer this question, but it does represent the options in a manner that helps you understand what you might do.

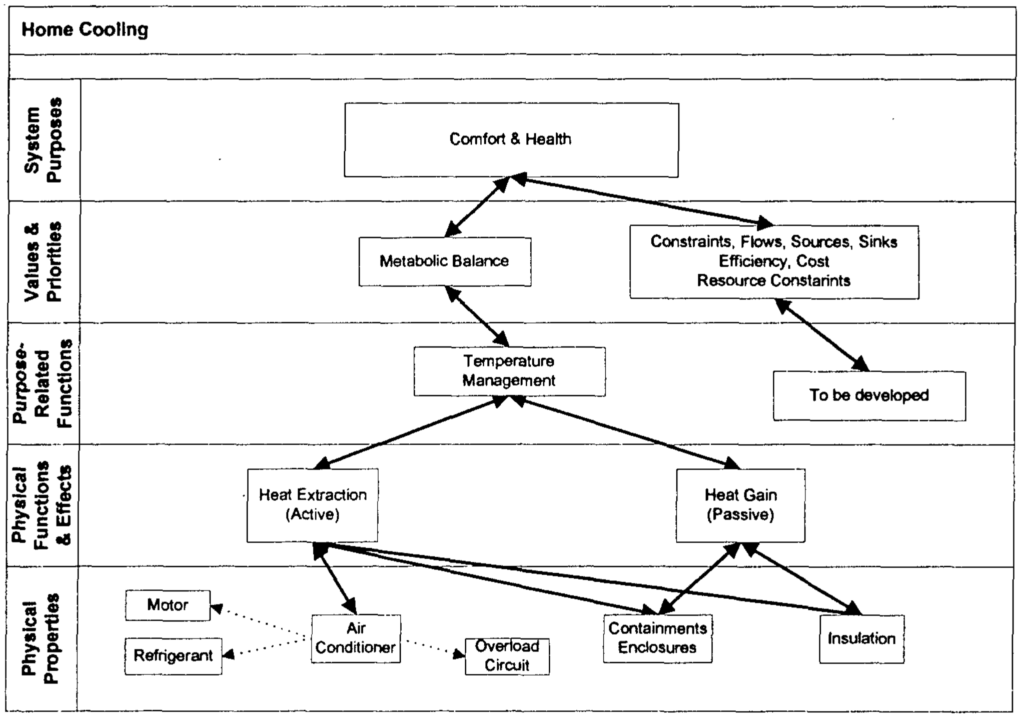

Figure A-5. An Abstraction-Decomposition map that shows some of the functional elements for home heating that contribute to comfort and health

AN ABSTRACTION-DECOMPOSITION MAP IS A DESIGN ARTIFACT

An Abstraction-Decomposition map is not a design or even a design specification but rather a design artifact. It organizes information in a systematic manner that will **support** design. For example, it can be used to specify the information requirements of a work domain. Each node in the Abstraction-Decomposition map points to information (either directly or indirectly) that must be provided within the workspace, although different stake-holders (staff members, operators) will need access to different constellations of that information. This information will reveal to the workers the essential functional properties (purposes, values, resources and opportunities) of their work area. However work remains beyond the development of the Abstraction-Decomposition map to generate the required design specifications.

AN EMPHASIS ON SOCIO-TECHNICAL SYSTEMS

Many who undertake Work Domain Analysis focus on the technical aspects of the systems they analyze but the central concern is with socio-technical systems and so the value of the analysis is limited to the extent that we do not consider the social aspects of the system. Figure A-6 contrasts a predominantly technical with a predominantly socio-technical analysis. An instruction from a procedures manual for librarians was used to develop the abstraction hierarchy in the right panel:

When a book is returned, draw a line with a black Magic marker through the name to protect the privacy of the borrower, replace the card in the book and then return the book to the shelf.

That abstraction hierarchy was developed as a tutorial exercise in making the design rationale for this instruction explicit. Why a magic marker? Why black? These become apparent in relation to the privacy issue but other types of markers may do as well. Or are there additional reasons? The general issue here is that design rationale is generally not made explicit in procedural specifications and workers can adapt without realizing they are violating the design rationale. The development of an Abstraction-Decomposition map is a step towards developing an explicit representation of design rationale that can be a made available to librarians so that they can respond not necessarily to the technical meaning of this instruction but to the intent behind it.

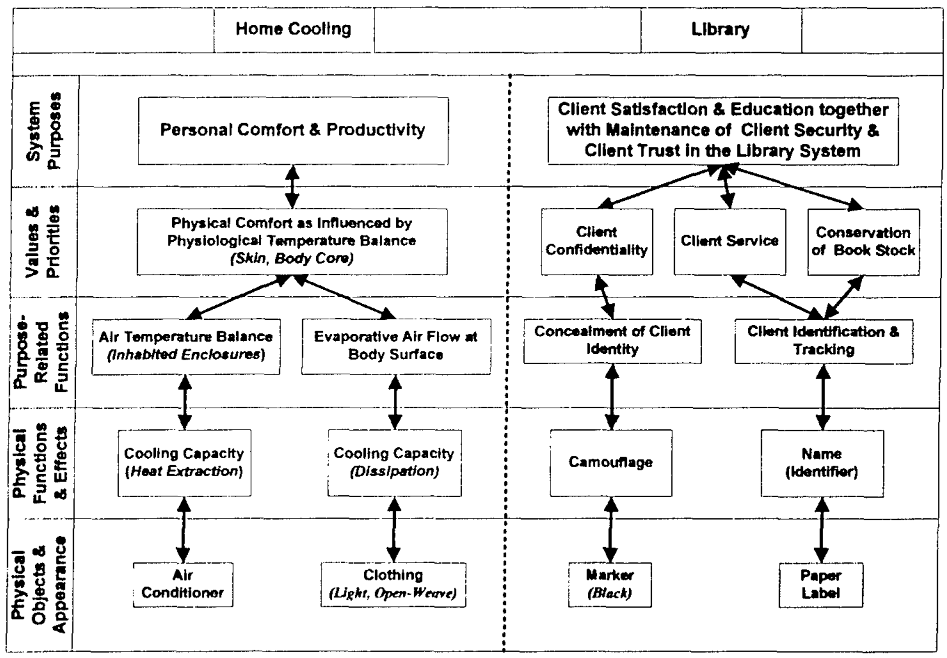

Figure A-6. Two tutorial examples of the Abstraction-Decomposition representation, a primarily technical system (Home Cooling, left panel) and a socio-technical system (Library Client Tracking, right panel)

SOCIO-TECHNICAL SYSTEMS HAVE STRANGE PROPERTIES

The functional properties of engineered systems are designed to be stationary. Non-stationarity intrudes when parts wear out but in the main, things stay the same. Such is not the case when we insert humans into the system. Humans change in themselves (they learn, they develop, they age) and they frequently modify the functionality of the systems they use. Many who undertake Work Domain Analysis focus on the technical aspects of the systems they analyze but there is added value in laying out those functional properties that are non-stationary because of human participation. Unlike the non-stationarity of technical systems, human-induced non-stationarity will often enhance system effectiveness and should be promoted rather than avoided.

The contrast of a predominantly technical versus socio-technical analysis as shown in Figure A-7 and Figure A-8 was developed to illustrate this point. The IPOD example is characteristic of many of the analyses found in the literature but the theatrical example illustrates a challenging feature of socio-technical systems that is often neglected. The functionality of the parts can change as the system evolves. The director might take on acting functions and actors might take on directing responsibilities. In addition, actors might develop and adapt their capabilities. For example, a comedy specialist might develop as a dramatic actor and over the life of an extended production might begin to inject dramatic elements into the performance. How does that change the system; in this case the theatrical experience for audience, performers and director?

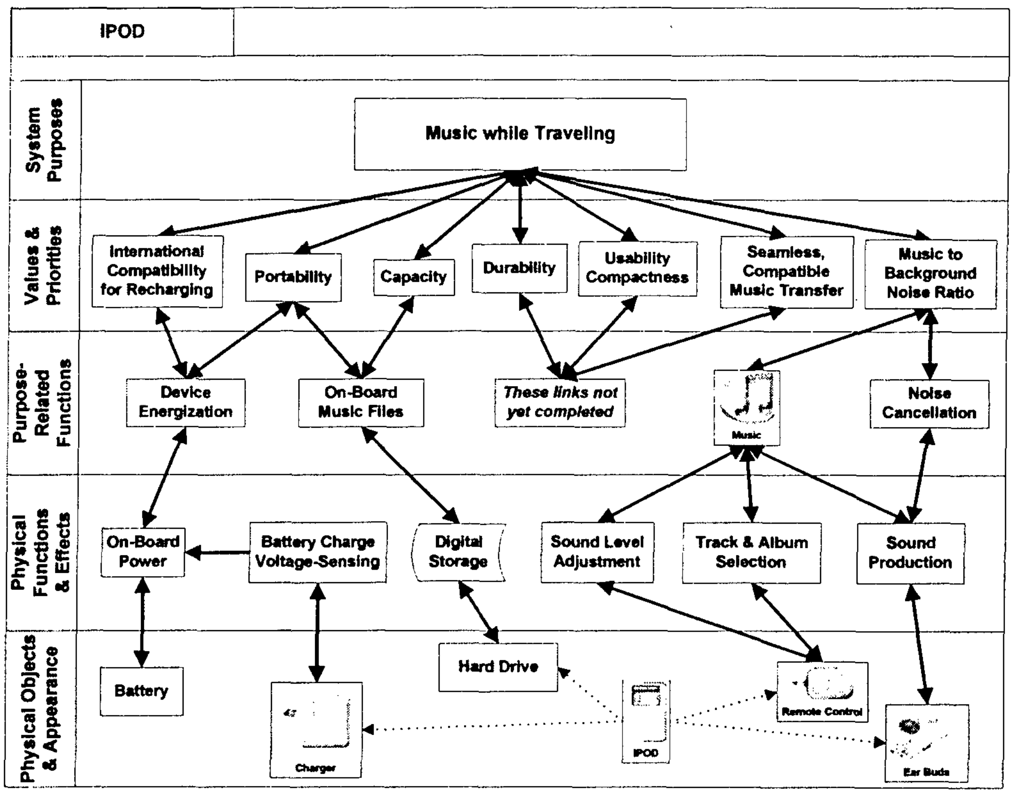

Figure A-7. A predominantly technical analysis of an IPOD

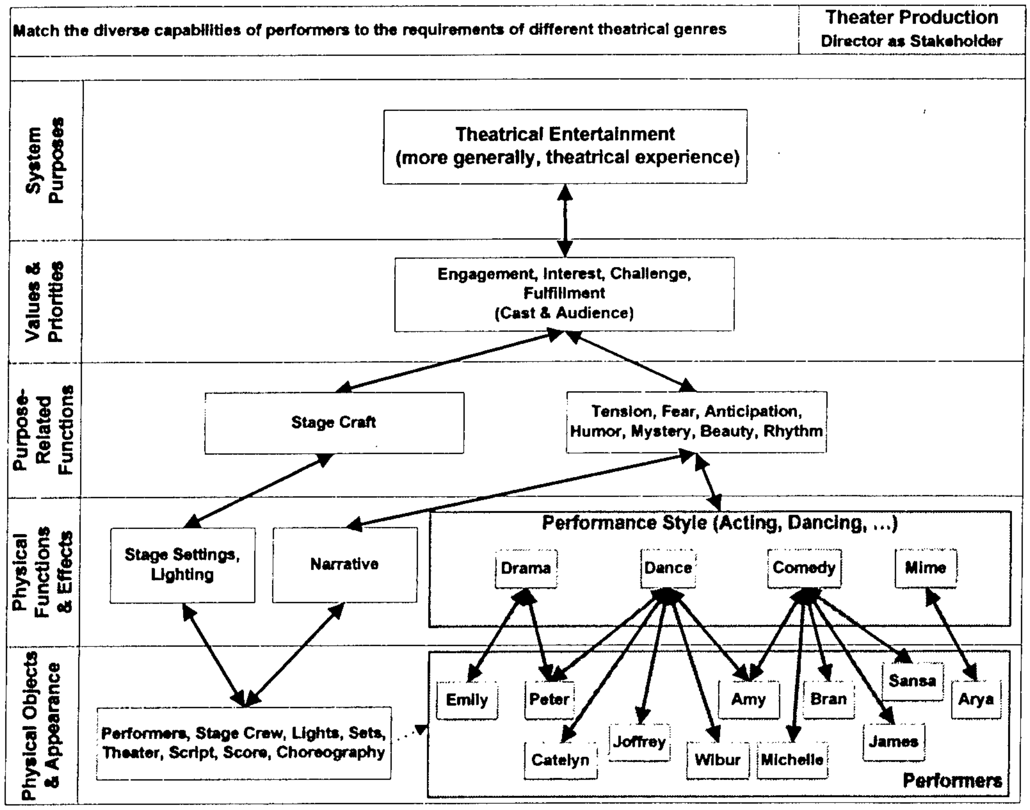

Figure A-8. A socio-technical analysis of a theatrical production

WHY ABSTRACTION-DECOMPOSITION?

Why might we believe that an Abstraction-Decomposition map is a useful form of representation? Jens Rasmussen has shown that expert trouble-shooters and expert problem-solvers navigate through an Abstraction-Decomposition space much like that represented in an Abstraction-Decomposition map as the solve problems. Typically, they start with purposes or values at the system level and then work down towards decompositions at physical object and physical process levels. Also, typically, the trajectory is irregular, opportunistic and iterative.

This pattern is depicted in Figure A-9 and Figure A-10 (from Hoffman and Lintern, 2006) where a fragment of a work domain for weather forecasters (Figure A-9) is overlaid with a scenario trajectory (Figure A-10). The numbers race the sequence in which one subject matter expert visited the nodes of the Abstraction-Decomposition map were within this scenario. The callouts reveal the comments made by the subject matter expert at each node.

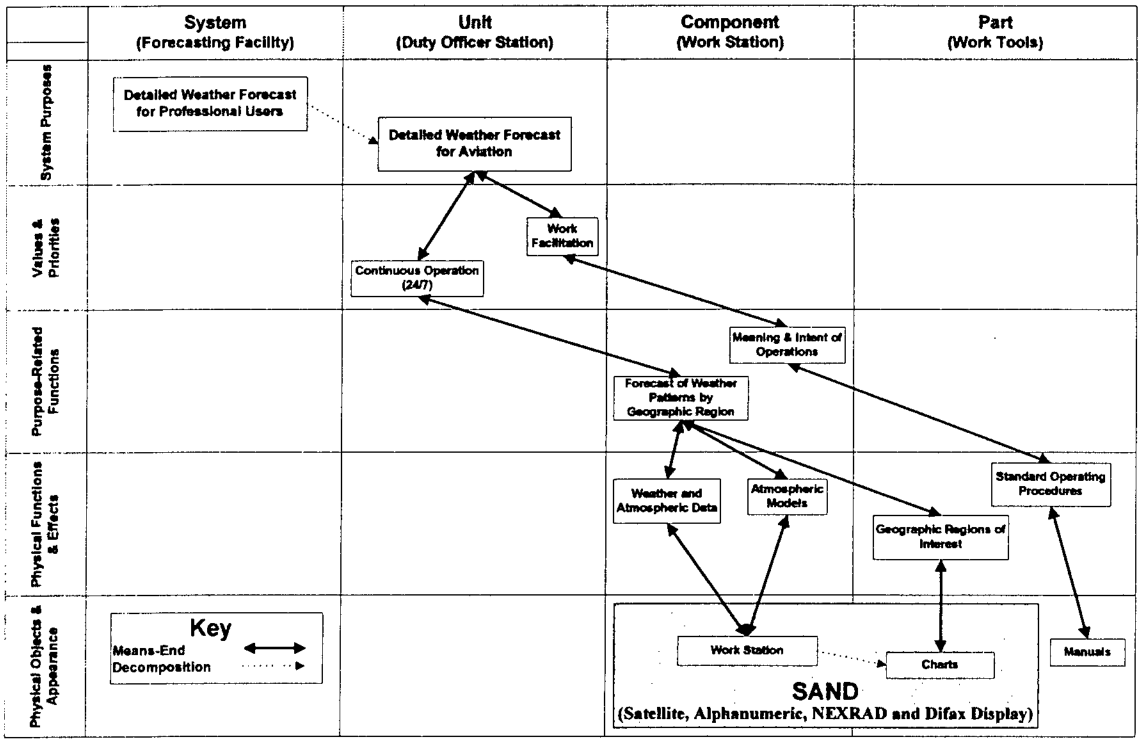

Figure A-9. An abstraction-decomposition matrix of a fragment of a weather forecasting work domain (From Hoffman and Lintern, 2006; Figure 12.2)

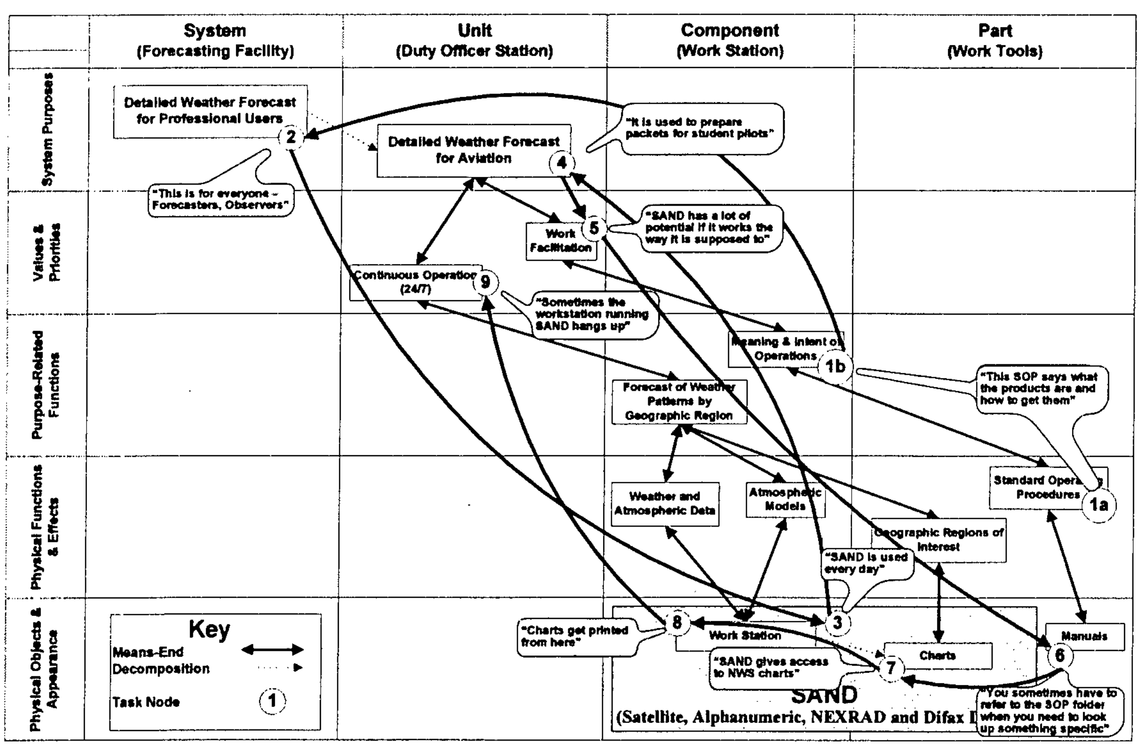

Figure A-10. An abstraction-decomposition matrix of a fragment of a weather forecasting work domain with an activity overlay (statements in callouts are quotes from a forecaster) (From Hoffman and Lintern, 2006; Figure 12.3)

The claim is that we all do that (at least implicitly) every time we solve a moderately complex problem. The commitment to the Abstraction-Decomposition space constitutes a theory of cognition, albeit one that has not yet been enunciated explicitly or in detail. Can you believe the claim that we navigate through an Abstraction-Decomposition space when we plan or solve problems? If you cannot, you probably should not build Abstraction-Decomposition maps. On the other hand, if you can believe that this is fundamental to the way people behave, you should find Work Domain Analysis to be a useful exercise. Furthermore, your understanding of that theory is your best guide to how you construct the Abstraction-Decomposition map; what the levels of abstraction mean, what sort of concepts go into each of those levels, and how you deal with decomposition.

Also remember that the Abstraction-Decomposition map is not a formal system as is, for example, mathematics. The elements of a formal system must be defined precisely and the relationships between them must be logical and consistent. Many of the critiques in the literature point to logical inconsistencies in the way that the various relationships of the Abstraction-Decomposition map are defined and used, but remember that this was never intended to be a formal system. It was always intended to be a depiction of the way subject matter experts could think effectively about their work domain. Many appear to believe that thinking processes correspond to formal computational processes but the underlying assumption of Work Domain Analysis is that the most effective forms of thinking are irregular, opportunistic and iterative; they are not irrational but they are very far from anything like a formal computational process.

THE RELATIONSHIP TO SYSTEMS ENGINEERING

Some Systems Engineers dispute the contribution of a Work Domain Analysis. They claim that this is a Systems Engineering tool that is already discussed adequately in standard textbooks. However, other Systems Engineers state that nothing like Work Domain Analysis exists within their discipline.

Decomposition is used extensively, systematically and explicitly within Systems Engineering (e.g., Blanchard and Fabrycky, 1990). In contrast, the commitment to functional abstraction is less clear. Tools such as Attributes Lists (which organize system features into the three broad categories of objectives, constraints and functionality), Hierarchal Objective Lists (which can be configured into Objective Trees) and Morphological Charts (also referred to as Function-Means Charts and Concept Combination Tables) are activity-independent analyses that use dimensions of classification somewhat like the abstraction dimension of Work Domain Analysis. Nevertheless, it is not clear that these tools are used widely or that their products are well integrated into the Systems Engineering process. In addition, although Systems Engineering texts refer to purposes and values, they do not clarify how those purposes and values should be integrated into the design of a system or how they might be implemented as constraints on design and use.

The magnitude of the intellectual debt owed Systems Engineering by Cognitive Work Analysis remains unclear, but of more concern is whether the products of Cognitive Work Analysis can be of value within the broad scope of the systems design process. The design of complex socio-technical systems continues to pose significant challenges, one of which is the effective deployment and use of human resources. Anything we can do as cognitive engineers to resolve those challenges will be of considerable benefit and the fact that the major concepts of Work Domain Analysis are already familiar to Systems Engineers is a point of contact between the two disciplines that should support rather than detract from this effort.

SOURCE MATERIAL

Blanchard, B. S. & Fabrycky, W. J. (1990). *Systems Engineering and Analysis* (2nd ed.). Englewood Cliffs, NJ: Prentice Hall.

Hoffman, Robert R. & Lintern, Gavan (2006). Eliciting and Representing the Knowledge of Experts. In Ericsson, A., Charness, N., Feltovich, P., & Hoffman, R. (Eds.) *Cambridge Handbook of Expertise and Expert Performance*. New York: Cambridge University Press.

Lintern, Gavan (2002). Brief: Cognitive Work Analysis. CTA eMagazine, December (http://www.ctaresource.com/eMagazine/)

Rasmussen, J., Petjersen, A. M. & Goodstein, L. P. (1994). *Cognitive Systems Engineering.* New York: Wiley.

Vicente, K.H. (1999). *Cognitive Work Analysis: Towards safe, productive, and healthy computer-based work.* Mahwah, NJ: Lawrence Erlbaum Associates.

APPENDIX B. WHAT DO THE ABSTRACTION LABELS MEAN?

BACKGROUND

This discussion of abstraction labels was developed by Dr. Gavan Lintern. Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defense Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering.

SYSTEM PURPOSE

The meaning of System Purpose is self-explanatory.

- What do we want to achieve with this system?
- Why does the system exist? Why is it being designed?
- *Purpose may be multi-dimensional.*

VALUES & PRIORITIES

What are the values that shape how you use this system, specifically how you use it to satisfy the purpose? What abstract properties help you establish priorities with respect to functional purpose? What are your guiding concerns?

- What considerations guide what you do? Most significantly, what considerations constrain how you set priorities and allocate resources?
- Properties of balance, conservation, preservation, minimization, maximization are important, e.g. safety-productivity tradeoff.
- Policies and Legislation will shape strategies, e.g. Rules of Engagement, Geneva Convention (what is the underlying value?)

A good way to view this; you get the job done, it works, all is fine, but you still think it is not a good job because you did not attend to certain details. The way you have done it is not elegant, it does not conform to the rules or it was risky. Others may not understand why you did it that way. You did not guard against potential problems. It worked this time but you were lucky.

PURPOSE-RELATED FUNCTIONS

These are the essential functions irrespective of physical nature of the system, e.g., communication with reference to System Purpose via Values and Priorities but without reference to the mode of communication.

- Plan, Organize, Inform, Maintain, Produce, Guide, Navigate, Generate, Communicate, Administer, Serve, Purchase, Exhibit, Mediate
- Properties sufficient to identify work domain functions that must be coordinated, regardless of how they are physically implemented, a meaningful combination of properties of the physical functions

PHYSICAL FUNCTIONS (& EFFECTS)

These are the specific functions of the physical elements of the system; the properties necessary and sufficient for control of physical work activities and use of equipment.

- <u>Find, Retrieve, Store, Position, Use, Talk, Signal, Lift, Push</u>
- The word **effects** is added because you might be concerned with the effects of the environment (e.g., weather). It sounds strange to say weather has a function although, conceptually at least, weather effects are similar to physical functions. Consequently, at this level, the term *function* is reserved for the consequences of engineered artifacts while the term *effect* is used to refer to the consequences of natural phenomena such as weather.

PHYSICAL PROPERTIES

Specify names of physical devices, colors, shapes, locations, etc. But only introduce descriptors that are relevant to your design purpose. For example, shape of an aircraft is not useful if you are designing a flight simulator for that aircraft but is useful if you are designing an aircraft identification system.

These are the properties necessary and sufficient for classification, identification and recognition of particular material objects and their configuration, and for navigation through the system.

TIPS

Tip for Identifying Physical Functions and Physical Properties

- Ask your subject matter experts what they would use to satisfy a Purpose-Related Function such as communication (*How would you communicate with your forward observer?*). Some may respond with an object (*I use the radio, the radar)* or they may respond with a physical function (*I send a message about this, I use the location and direction of the target)*. To the object response, you ask *what does it do*? To the physical function response you ask, *what system gives you that*? Record both and link them.

Tip for Decomposing

- **Decompose** to level of possible action

Tip for the early stages of system design

- You might only need to develop the top three levels of the abstraction hierarchy.

APPENDIX C. REPRESENTATIONAL ISSUES AND REPRESENTIONAL FORMS

BACKGROUND

The following commentary reflects Dr. Lintern's perspective of representational issues and representational forms in Cognitive Systems Engineering. Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defense Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering.

REPRESENTATIONAL ISSUES

Issue: Tightly-Coupled Control

It is a major concern that almost all representations used by Systems Engineers and Cognitive Engineers imply tightly coupled control. The dangers of tightly coupled control within human endeavors are well known; it is often referred to as micro-management and is the reason that work unions can impose the seemingly odd tactic of a work-to-regulations strike (Lintern, 2003). Following an exceptional analysis of a major system accident, Snook (2000) recognized the danger but apparently could not envision an alternative. Tightly coupled control of systems that include humans as functional components are prone to instability. Although that is now well known, many in Cognitive Systems Engineering—who will readily deny any commitment to tightly coupled control in personal conversation (e.g., Erik Hollnagel, David Woods, Kim Vicente)—continue to make occasional statements in their published work (Hollnagel & Woods, 1999; Vicente, 2004) and in their professional presentations that are most readily taken to imply that commitment.

This problem almost certainly results from the now long-established practice of looking towards technology for images of mechanism (e.g. the computer) to support our understanding of how cognitive systems work. In contrast, the single most significant contribution from Cognitive Engineering towards understanding human behavior is the radical move by its founders (e.g. Klein, 1989; Rasmussen, 1986) of looking towards the details of human work activity and human work experience for insightful images. This move is not well recognized even among practitioners of Cognitive Engineering. Some, for example, argue that interest in cognitive issues is the defining contribution of Cognitive Engineering, and accompany that observation with the spurious claim that Human Factors and Engineering Psychology do not deal with cognitive issues (e.g., Hollnagel & Woods, 1999).

Issue: Decomposition

> *The focus in the past has been on the Cartesian approach of breaking a problem into smaller components, solving each of the smaller problems, and then integrating the pieces back into a whole solution.*
>
> International Council on Systems Engineering (2005)

Decomposability has been the basis of standard engineering design practice, which in itself provides one of the challenges to Human Systems Integration. The assumption that technical systems can be disassembled into independent modules is conceptually safe because engineered systems are fabricated from independent modules; essentially that has always been the dominant design strategy. In contrast—and despite what one commonly sees in textbooks by cognitive psychologists—the human cognitive system is not decomposable; the attempt to decompose the human cognitive system results in modules that are interdependent, a fact often appreciated by those who do the decomposition and who attempt to deal with this issue by the use of a dense network of feedback and feed-forward loops. Unfortunately, that representational strategy implies tight coupling, which is definitely not the characteristic mode of interaction within the human cognitive system. Furthermore, the insight that can be derived from a representation in which modules represent arbitrary decompositions and every node is connected to every other node is limited.

REPRESENTATIONAL FORMS

Abstraction-Decomposition

Practitioners of Cognitive Work Analysis are occasionally criticized for their emphasis on Work Domain Analysis, it often being the only phase of Cognitive Work Analysis that is completed. In their recent book, Burns and Hajdukiewicz (2004) ignore the remaining four phases on their way to developing an approach to Ecological Interface Design. Although this emphasis might be seen as a weakness, it has resulted in the relative maturation of Work Domain Analysis and its analytic product, the Abstraction-Decomposition matrix. Concerns remain, most notably in the definition of terms that are central to the construction of an Abstraction-Decomposition matrix, but considerable value has accrued in terms of product maturation from this focus on the Work Domain Analysis.

Decomposition is used extensively, systematically, and explicitly within Systems Engineering (e.g., Blanchard and Fabrycky, 1990). In contrast, the commitment to functional abstraction is less clear. Activity-independent analyses that use dimensions of classification somewhat like the abstraction dimension of Work Domain Analysis (e.g., Attributes Lists, Hierarchal Objective Lists and Morphological Charts) are available, but it is not clear that they are widely used or that their products are well integrated into the analytic processes of Systems Engineering. For example, the Department of Defense architectural framework does not include a dimension of abstraction in any of its 26 different forms of representation (DOD Architecture Framework Working Group, 2004).

Abstraction is a challenging concept. The potential contribution of the abstraction dimension may be little appreciated because it is poorly understood and is readily confused with decomposition. Sarcedoti (1974) is one who—in proposing a hierarchy of abstraction spaces as a means of reducing combinatorial complexity for planning—appears at first to appreciate the contribution of an abstraction analysis. However, having outlined this proposition, Sarcedoti then proceeds to treat abstraction in terms of decomposition. Similarly, Ayn Rand uses abstraction as a key idea in support of her Objectivist Epistemology, but she also confuses abstraction with decomposition (original papers by Ayn Rand, republished in Binswanger & Peikoff, 1990)

Indeed, this is an issue that those of us who develop Abstraction-Decomposition matrices have faced. Almost without exception, we have struggled in our early experiences with Work Domain

Analysis to resist the temptation to decompose along the abstraction dimension, to build what would essentially amount to a Decomposition-Decomposition matrix. The distinction between abstraction and decomposition is logical but not obvious, and those who analyze complex socio-technical systems will not turn their attention to it unless encouraged to do so. This is possibly a significant contribution that Cognitive Engineers can make to Systems Engineering practice.

Subsumption

Subsumption is a hierarchical structure in which activities at a subordinate level are subsumed under a super-ordinate activity. The relationship between the super-ordinate and subordinate activities is one of supervisory management; the super-ordinate activity initiates, monitors and terminates the subordinate activity—but beyond that, the subordinate node is autonomous (management, not control).

- The subsumption architecture may extend over several levels.
- Adjacent levels require two-way communication; supervisory management flows from super-ordinate to subordinate, and status updates and product delivery flow from subordinate to the super-ordinate.
- One super-ordinate node may manage many subordinate nodes.

A representational form based on subsumption architecture captures many noteworthy aspects of cognitive work within a complex, socio-technical context, and does so more coherently than does a representational form based on the ubiquitous linear-flow model. A subsumption representation implies a coordinated coalition. The separate activities are initiated as needed—sometimes simultaneously and sometimes overlapping. Different activities may sometimes be active, then inactive, and then active again, as managed at the supervisory level.

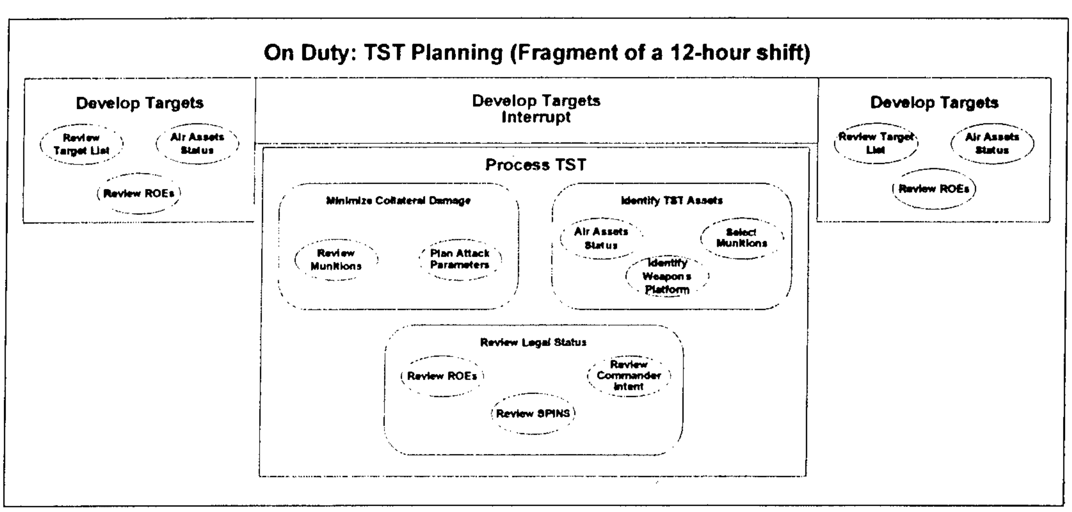

Figure C-1. A three-level subsumption representation of Time Sensitive Target planning in which background activities are interrupted by the arrival of a high priority task and resumed when that task is completed.

Subsumption depicts workflow as a composition (versus a causal sequence) of behaviors acting independently but orchestrated as a coherent performance on the basis of supervisory priorities.

It permits a meaningful representation of distributed supervisory management and can capture essential elements of both individual and team (distributed) behavior as in:

- Activities remain coherent even if the context changes; emerging and changing needs can be accommodated.
- Supervisory management (versus micromanagement); how management can communicate with subordinate entities and how it can coordinate their efforts (an issue for all distributed cognition and the essence of teamwork) so that those who execute are given the freedom to exploit their strengths as they contribute to the common goal.
- Interrupt and resume activities, which are ubiquitous within socio-technical work, are handled conveniently by having all subordinate nodes active and in competition for time so that a super-ordinate node may suspend or abort an active subordinate node and activate another to simulate adaptive or flexible adjustment to changes in context or knowledge (Figure C-1).

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APPENDIX D. THE RELATIONSHIP OF COGNITIVE ENGINEERING TO SYSTEMS ENGINEERING

Background

This discussion was developed by Dr. Gavan Lintern. Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defense Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering.

Discussion

Some Systems Engineers dispute the contribution of a Work Domain Analysis. They claim that this is a Systems Engineering tool that is already discussed adequately in standard textbooks. However, other Systems Engineers state that nothing like Work Domain Analysis exists within their discipline.

Decomposition is used extensively, systematically and explicitly within Systems Engineering (e.g., Blanchard and Fabrycky, 1990)[9]. In contrast, the commitment to functional abstraction is less clear. Tools such as Attributes Lists (which organize system features into the three broad categories of objectives, constraints, and functionality), Hierarchal Objective Lists (which can be configured into Objective Trees) and Morphological Charts (also referred to as Function-Means Charts and Concept Combination Tables) are activity-independent analyses that use dimensions of classification somewhat like the abstraction dimension of Work Domain Analysis. Nevertheless, it is not clear that these tools are used widely or that their products are well integrated into the Systems Engineering process. In addition, although Systems Engineering texts refer to purposes and values, they do not clarify how those purposes and values should be integrated into the design of a system or how they might be implemented as constraints on design and use.

The magnitude of the intellectual debt owed Systems Engineering by Cognitive Work Analysis remains unclear, but of more concern is whether the products of Cognitive Work Analysis can be of value within the broad scope of the systems design process. The design of complex socio-technical systems continues to pose significant challenges—one of which is the effective deployment and use of human resources. Anything we can do as cognitive engineers to resolve those challenges will be of considerable benefit and the fact that the major concepts of Work Domain Analysis are already familiar to Systems Engineers is a point of contact between the two disciplines that should support rather than detract from this effort.

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[9] Blanchard, B. S., & Fabrycky, W. J. (1990). *Systems Engineering and Analysis* (2nd ed.). Englewood Cliffs, NJ: Prentice Hall.

APPENDIX E. A DISCUSSION WITH DR. GÜL KREMER REGARDING HOW COGNITIVE ENGINEERS MIGHT SUPPORT SYSTEMS ENGINEERS

BACKGROUND

The discussion reported below took place between Dr. Lintern and Dr. Kremer on 13 March 2005 at Pennsylvania State University.

Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defense Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering.

Dr. Gül Kremer is an Assistant Professor of Engineering Design, Pennsylvania State University. She was a Summer Faculty Fellow at the Air Force Research Laboratory's Human Effectiveness Directorate in 2002, 2003, 2004, and 2005.

DISCUSSION

What are the important cognitive issues?

This is not self-evident and many of the cognitive issues on which people focus, such as those relating to interface design, are not the most critical. We should be addressing those that face systems engineers early in the design phase, particularly in the concept definition phase, for example:

- How might we incorporate load issues relating to fatigue? How long can people stay on the job? What are the handover costs?
- How do we make resource assignments?
- How can we automate support decisions and what interface should be used?
- What level of operator intervention should we achieve—the operator has to enter into the decision points at critical gates—so what are the critical decision points?
- Visualization—operators emphasize the common operating picture—can we develop a visualization that will help them make their decisions?

We discussed the need for a design case study that will put together the design requirements to realize operational needs. The purpose would be to allow examination of *what-if* scenarios to reveal bottlenecks.

Workload

How might we reveal to a systems engineer how operator workload would affect a proposed design? For physical issues, there are tables to show how well people can work under load. Systems engineers are fond of this sort of thing and one thought we explored is that we might develop nomograms for workload or time demands of a task or activity. Nevertheless, this would appear to be an optimistic project. There is, as yet, no standard way of measuring workload and even if we were to settle on a standard procedure, we will still often need to assess workload for systems for which there is no prototype on which the tasks can be examined.

Time, when used to assess performance, does not have the same measurement problem as workload—but again, assessment of the demand (how long an activity will take to perform) is a challenge. As an example of a problem, consider the activity of original cataloging within a library. Cataloging comes in two basic forms. Copy cataloging is the process of taking an existing record and adapting it for the specific library's purpose. Original cataloging is more demanding. It requires that the cataloguer generate an entirely new record. The cataloguer creates that record based on the understanding gleaned from examination of the source document. The creation of an original record can take anywhere from several minutes to several hours. The huge difference in time results because of the following factors:

- the difficulty and clarity of the source material
- the experience of the cataloguer both in terms of general experience and in terms of specific experience with the domain in question
- the stated requirements for specificity and detail—research libraries, for example, require more specific and detailed records then do public libraries
- the response speed of the cataloging system, which may vary from day-to-day and throughout the day (most cataloging is done on networked systems, many of which are shared by a network of libraries)

Probably the only way to anticipate how long something like original cataloging would take to accomplish would be to decompose the activity into sub-tasks and then develop a model that would take into account the various contingencies and complexities.

What are we trying to achieve?

Almost all of the discussions about how Cognitive Engineers might support Systems Engineers take, as a starting point, the need to represent cognitive knowledge in a form that Systems Engineers can understand and also integrate within their own style of developing system design specifications. I wish to propose a different perspective that we might explore over the coming months; that we should be developing simulation environments that permit Systems Engineers to explore the cognitive ramifications of their design solutions. My motivation for proposing this alternate approach is that I believe it is unrealistic to think that we can specify cognitive parameters with precision sufficient to aid the design effort of Systems Engineers.

Consider the possibility that the biggest challenge facing systems engineers as they formulate a system concept is that they know very little about work structure or process. The information that might help them develop an effective system might be gained from extensive experience within a working system prototype. The regularly-scheduled tests of Air and Space Operations Center processes (Joint Expeditionary Force Experiments or JEFX) might offer such opportunities, but are hugely expensive and difficult to conduct. In addition, that system is far too complex. Simple human-in-the-loop simulations, such as the procedure of tabletop analysis used by Naikar, Pearce, Drumm and Sanderson (2003)[10] would also appear to offer an opportunity, but this sort of analysis requires technical skills that systems engineers typically do not have (see Appendix F for a discussion of tabletop analysis).

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[10] Naikar, N., Pearce, B., Drumm, D. & Sanderson, P. M. (2003). Technique for designing teams for first-of-a-kind complex systems with cognitive work analysis: Case study. *Human Factors*, 45(2), 202-217.

I propose that the solution lies in the development of an appropriate dynamic simulation process model for the system under consideration. The model would essentially replicate the process of tabletop analysis as used by Naikar et al. (2003). The content of the model would still have to be developed via a procedure like tabletop analysis and so would require an intensive effort by a suitably trained Cognitive Engineer, but once developed it could be used by others to explore the parameter space. This offers the significant advantage of being the type of tool with which Systems Engineers would typically be comfortable. In addition, once the time-consuming process of model development has been completed, many parametric variations could be examined with much less effort. Such is not the case with tabletop analysis.

I wish to stress at this point in that the proposed modeling effort is not one that is aimed at identifying cognitive parameters—but is aimed specifically at providing the Systems Engineer as designer with the sort of experience that will promote sensitivity to and appreciation of the important cognitive issues that have to be considered in design. This purpose is consistent with the use of tabletop analysis by Naikar et al. (2003). Although parameter specification might seem a desirable goal, I currently view it as an unrealistic one. On the other hand, it does seem realistic that we could help a designer develop an appreciation of the significance of parametric variations within different dimensions, and I propose that such a result would generate a far more robust design strategy than is the case currently.

Representational Forms

An assumption of this project is that the product of any cognitive analysis should be provided as a representation. Nevertheless, the appropriate form of representation is in question. A preliminary example of one representational form is shown here as Figure E-1. To this point, it shows few details, but the idea here is that this is the sort of form that would be desirable as the output of a human-in-the-loop tabletop analysis or of a computer model. Ideally, a computer model would show the progress of activity in a dynamic, unfolding fashion and would depict communication events in a time sequence. Figure E-1 shows a node structure only for the human agents and would therefore reveal only the human-human interaction. A complementary representation of a node structure for system functions is also necessary to depict the human-technology interactions.

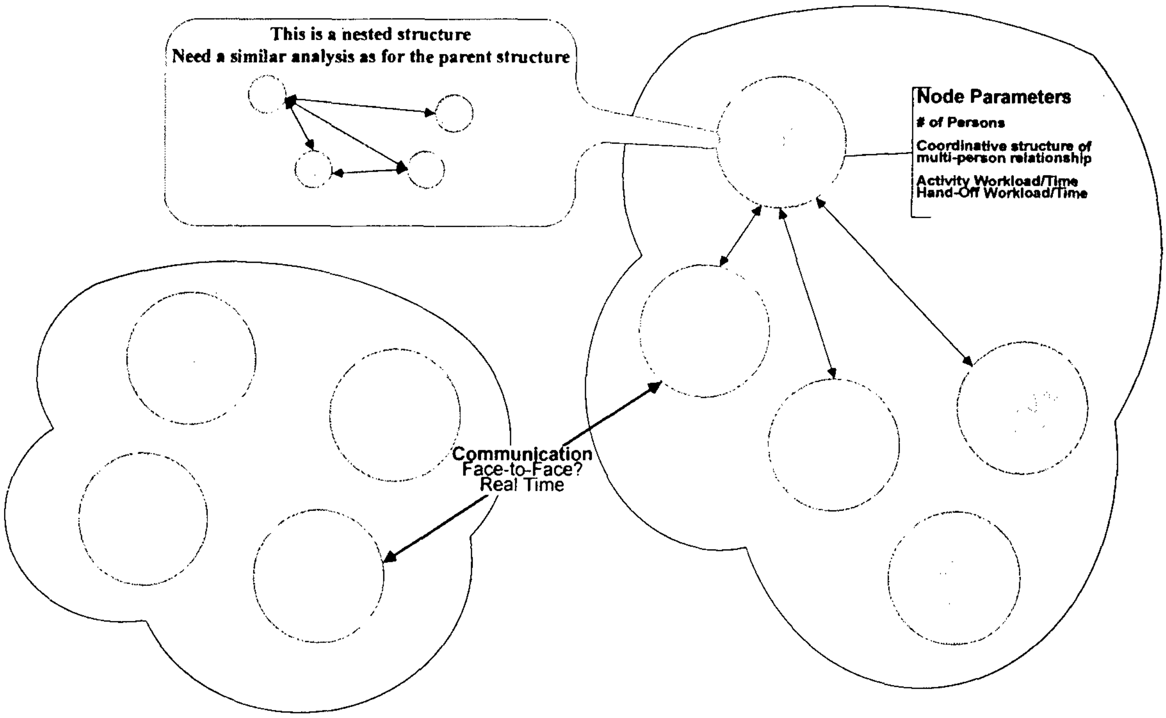

Figure E-1. Communication flow diagram

APPENDIX F. DR. NEELAM NAIKAR'S APPROACH TO TABLETOP ANALYSIS

Background

The discussion notes reported below are from Dr. Lintern's interview with Dr. Naikar regarding tabletop analysis. This discussion took place at the Australian Defence Science and Technology Organisation on 25 January 2005.

Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defence Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering.

Dr. Neelam Naikar is a Cognitive Engineer with the Defence Science and Technology Organisation (DSTO), Melbourne, Australia.

Discussion

Tabletop analysis starts with a design scenario, developed through discussion with subject matter experts that captures the extremes of work intensity in terms of cognitive demands and workload (something we termed "edge cases". The design scenario identifies the representative and prototypical features of a coalition environment. Importantly, it identifies prototypical features, typical geography, and timelines for work activities.

Subject matter experts are sat before a map over a relevant area, with all entities located at a specific time. They are given a brief technical summary describing key events at that time. The researchers and the subject matter experts then discuss the unfolding of events of the scenario over successive time periods, relocating entities as necessary and talking about the activities as they relate to the events.

There are two subject matter experts per scenario analysis. They are asked about how they would allocate work to crewmembers and what crew concept they would like to use as they move through the time periods of the scenario.

Neelam stressed that the purpose was not to evaluate crew concepts or performance of crews in various configurations, but was more for generating a debate that would clarify the important dimensions or properties of teams. Thus, tabletop analysis is not about testing team design but about exploring the issues (e.g., if we have a multi-skilled team that reconfigures for different challenges, the mission commander needs to devote resources towards management).

From this notion, Neelam and I discussed the sort that cognitive representations to be designed to help systems engineers with cognitive demands problems. These representations should not necessarily be aimed at specifying the cognitive demands and the design solutions, but should be aimed at supporting a dialog between cognitive engineers and systems engineers as they seek to resolve design issues surrounding cognitive requirements.

APPENDIX G. COMMENTARY ON DR. LIND'S CRITICAL ANALYSIS OF ABSTRACTION-DECOMPOSITION ANALYSES

BACKGROUND

The following is Dr. Lintern's commentary on a critical analysis of Abstraction-Decomposition analyses published by Dr. Lind in 2003.

Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defense Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering.

Dr. Morten Lind is a Full Professor of Control Systems Engineering at the Technical University of Denmark, Lyngby, Denmark. His research interests include human-machine systems for supervisory control and modeling of complex socio-technical systems. From the late 1960s to the early 1980s, he served as a Research Scientist at the Risø National Laboratory, Roskilde, Denmark. He later consulted for the Risø National Laboratory's Cognitive Systems Group in 1994.

ABSTRACT

Lind (2003) has authored a critical analysis of the Abstraction-Decomposition analysis undertaken in Cognitive Work Analysis. I review his critique and conclude that it is misguided in many aspects. In my analysis, I touch on issues related to Multilevel Flow Modeling and Applied Cognitive Work Analysis. Abstraction-Decomposition analysis has a unique role to play within Cognitive Engineering. Although only some of the issues raised by Lind require resolution, consideration of those selected issues would be useful for the development of Cognitive Work Analysis.

INTRODUCTION

Morten Lind was involved with Jens Rasmussen[11] in the early developments of Cognitive Work Analysis, but became disenchanted at least with Work Domain Analysis. He subsequently developed Multilevel Flow Modeling to address the issues he sees as important for Human-Systems analysis. Multilevel Flow Modeling retains some elements of an Abstraction-Decomposition analysis but differs from it in substantive ways.

Lind (2003) raises several challenges for Work Domain Analysis. I review those challenges to assess:

- whether his critique for the Abstraction-Decomposition format developed within Work Domain Analysis has value, and
- whether we should be taking notice of Multilevel Flow Modeling.

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[11] Jens Rasmussen was a professor of Cognitive Systems Engineering at the Risø National Laboratory and the Technical University of Copenhagen. He has conducted research in the areas of human reliability, work domain taxonomy, human-system integration, and ecological information systems design. He currently consults in Cognitive Systems Engineering.

I have reviewed four of Lind's papers and have engaged in an e-mail exchange with him. This note summarizes my conclusions. In addition, a small number of the arguments found in papers that describe Applied Cognitive Work Analysis (e.g. Elm, Roth, Potter, Gualtieri & Easter, 2005) are similar to those forwarded by Lind and there is some similarity between Multilevel Flow Modeling and the Functional Abstraction Network of Applied Cognitive Work Analysis. I note that where it is relevant.

Overview

Work Domain Analysis is a phase of Cognitive Work Analysis, which in turn is a framework within the larger enterprise of Cognitive Systems Engineering. I have begun to prefer the term Abstraction-Decomposition analysis for Work Domain Analysis because the Work Domain Analysis normally undertaken within Cognitive Work Analysis is only one of potentially many ways to analyze the work domain. Burns and Vicente (2001) note, for example, that Multilevel Flow Modeling is a form of Work Domain Analysis.

Lind has emerged as notable critic of Work Domain Analysis as practiced within the Cognitive Work Analysis framework, primarily directing his critique at the Abstraction-Decomposition format and the means-ends connections between levels of abstraction. In summary, he argues that an Abstraction-Decomposition analysis is incoherent and cannot perform the role promoted for it by Rasmussen, Vicente, and many others (including me), either in principle or in practice.

Lind is not alone in voicing his disapproval of the Abstraction-Decomposition analysis but, in contrast to many others whose critiques are little more than expressions of discontent, he has developed an argument with content. His arguments are sufficiently cogent to be addressed and, given that they are devastating if valid, need to be addressed by those of us who practice Work Domain Analysis in the form espoused by Rasmussen and Vicente. Lind's arguments are not relevant to Applied Cognitive Work Analysis (Elm, et al., 2005), which does not lead to an Abstraction-Decomposition map and which, in fact, leads to a representation similar to that produced in Multilevel Flow Modeling. Elm, Potter, Gualtieri, Roth and Easter (2003) acknowledge their intellectual debt to Lind.

Lind presents his most comprehensive critique in his 2003 paper, which is essentially a development of an earlier symposium paper (Lind, 1999a). He argues that the Abstraction-Decomposition analysis suffers from both methodological and conceptual problems—specifically that the meaning of the abstraction levels and the means-ends relations between them are not well defined and that there is no rationale for a fixed number of abstraction levels. He concludes (essentially without justification) that clarification of *the semantics of the abstraction hierarchy will invariably reduce the range of work domains* to which it can be applied. There is far too much in Lind's 2003 paper to deal with everything, but in what follows, I will address what I see as the most challenging issues.

ASSESSMENT STRATEGY

The best criterion for assessing the effectiveness of an analytic method is its effectiveness in supporting the project in which it is being used. That is generally difficult because the results of analysis are often not transformed into design and at other times, the link between a design and the preliminary analysis remains obscure. Assessment of an analytic method is particularly troublesome when it is used predominantly in the design of systems that are to be fielded at some considerable time into the future. In that case, analysis must proceed in the absence of operational feedback—and even after a system is fielded it may be difficult to connect operational success or failure to the design techniques used in development.

Where analysis is directed at future systems, a critique of the principles and structure of the analytic method can be useful if it reveals one or more of the following problems, listed in order from the most to least serious:

- The method is poorly motivated and has nothing to offer even if done well,
- The basic principles are fatally flawed and although the method is well motivated and without a challenger, it cannot accomplish anything useful,
- There is a different analytic strategy that will accomplish what that method is supposed to accomplish but does it more effectively,
- The basic principles of the method are sound and the method itself well motivated, but in use, practitioners do not apply the principles properly and the method does not live up to its potential.

For Lind's critique to have any value, it must establish that Abstraction-Decomposition analysis fails on at least one of these criteria. I have concluded from my review of his papers that he believes the method is well motivated but that its basic principles are fatally flawed. In what follows, I will first assess the merit of his argument in relation to that *fatal-flaws* criterion.

FATAL FLAWS

Abstraction-Decomposition analysis is, as the term implies, an analytic method and must therefore be coupled with a design or development strategy to achieve a pragmatic result. Ecological Interface Design is the design strategy of choice. Vicente (2002) has reviewed the contributions of Ecological Interface Design and has concluded that progress has been encouraging, and that there is evidence both of applicability to a diverse set of operational domains and of technology transfer to industry. Vicente's review shows explicit links between Abstraction-Decomposition analysis and Ecological Interface Design for at least some of his examples. When coupled with work outside the Ecological Interface Design realm by Naikar, Pearce, Drumm, and Sanderson (2003) and Naikar and Sanderson (2001) relating to design of complex operational systems, the support for Abstraction-Decomposition analysis is persuasive.

Any argument for fatal flaws would have to demonstrate how these projects achieved successful outcomes in spite of—rather than because of—their reliance on Abstraction-Decomposition analysis. Lind (2003) did not examine any of the projects reviewed by Vicente, nor did he assess the work of Naikar and Sanderson (2001). Doubtless, the work of Naikar et al. (2003) was published too late to for him to evaluate in his paper, but it also undermines his critique. In the absence of any substantive argument that can discount Vicente's conclusions or the relevance of the work by Naikar and Sanderson (2001) and Naikar et al. (2003, I discount the *fatal-flaws* argument.

Nevertheless, it would be useful to examine the content of Lind's arguments in light of a less stringent criterion noted above; that the method does not live up to its potential because application of its principles is inconsistent. That exercise may serve to draw some value from Lind's critique by making the principles more explicit. I am unaware of any alternative method for mapping workplace structure and therefore do not examine the possibility that there is a more effective alternative.

TERMINOLOGY

I like to refer to the product of an Abstraction-Decomposition analysis as an Abstraction-Decomposition map, an Abstraction-Decomposition space or an Abstraction-Decomposition representation. Elsewhere, it is known as an Abstraction Hierarchy or an Abstraction-Decomposition model. The term *Abstraction Hierarchy* is unsatisfactory because it encourages neglect of the decomposition dimension, which is essential to this analysis. I dislike characterizing this as a *model* because to many the word *model* implies properties that the result of this analysis does not capture, for example properties of causality and activity. That is not to argue that *model* is incorrect when used in this sense, but only that it introduces avoidable ambiguity.

Lind (2003) refers to means-ends and part-whole abstractions. Abstract means *to consider apart from concrete existence* (Houghton Mifflin, 2000). There are numerous ways of abstracting a domain, and the means-ends relationship defines one of them. Neither assembly from parts (composition) nor disassembly into parts (decomposition) constitutes a gradation from concrete existence, and should not be characterized as an abstraction. To speak of a *part-whole abstraction* suggests a failure to grasp the essential nature of abstraction.

The belief that cognitive activity maps to an Abstraction-Decomposition structure in a specific and significant way is one of the foundations for Cognitive Work Analysis. Both Rasmussen and Vicente argue that experts navigate through an Abstraction-Decomposition space as they troubleshoot or solve problems. I believe that much of the confusion and skepticism about the Abstraction-Decomposition analysis emanates from a failure in the community that practices Cognitive Work Analysis to develop and stress this idea. I suggest that if we were to develop and establish this idea beyond the cursory treatment given it by both Rasmussen and Vicente, the sense of the Abstraction-Decomposition analysis would become more widely apparent. I do not, however, focus on that issue in this note.

I have long suspected that some of the skepticism I encounter regarding the Abstraction-Decomposition analysis results from confusion about what is meant by ***hierarchy*** and ***network*** and I take the opportunity here to clarify those terms.

A ***hierarchy*** is a system of ranking and organizing things in terms of a relationship, such as *is superior to*, *is part of*, or *is taller than.* A node at a higher level of a hierarchy is designated as *superior* to nodes to which it is linked at a lower level, and those lower-level nodes are designated as *subordinate.* A hierarchy is:

- transitive—if *a* is *superior* to *b*, and *b* is *superior* to *c*, then *a* is *superior* to *c*
- irreflexive—no entry in the hierarchy is *superior* to itself
- asymmetric—if *a* is *superior* to *b*, then *b* is not *superior* to *a*

Most hierarchies conform to the property of *containment* in which subordinate nodes are strictly nested within superior nodes (Figure G-1, left panel) but a functional abstraction hierarchy does not conform to this property; subordinate nodes need not be contained by (linked to) only one superior node (Figure G-1, right panel). Relaxation of the containment property allows us to track multiple (sometimes unintended and undesirable) effects of subordinate nodes and is crucial to effective use of means-ends relationships for design of socio-technical systems. For this reason, we should speak of *means-ends* rather than *means-end relations*.

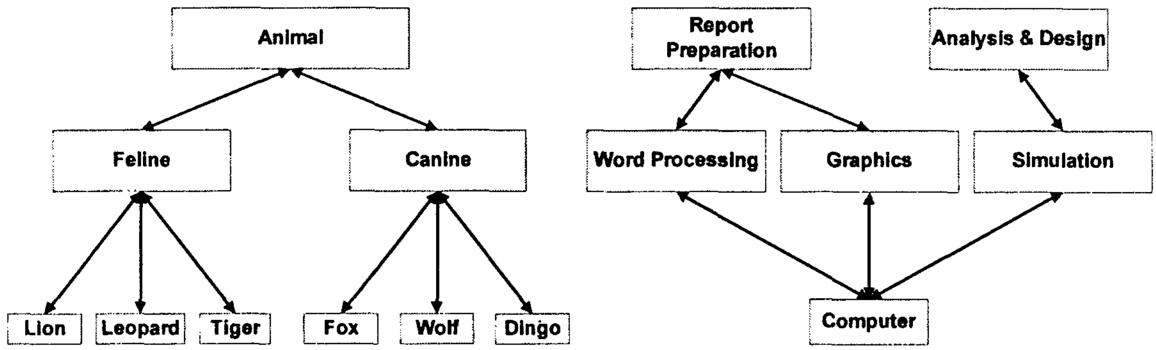

Figure G-1. Hierarchies generally conform to the property of containment (left) but a functional abstraction hierarchy does not (right).

The classification hierarchy of Figure G-1 (left panel) is also an abstraction hierarchy of the type used as a foundation for Ayn Rand's Objectivist Epistemology (Rand, 1979/1990). The Abstraction-Decomposition analysis of Cognitive Work Analysis is about functional abstraction and functional decomposition. In discussion, the term functional is often left implicit to avoid the repetition of a long and clumsy designation, but it should not be forgotten.

A ***network*** is an interconnected arrangement of elements. The nodes may be connected in either a regular or an irregular pattern (e.g., a network of railroads, an espionage network, an extended group of people with similar interests or concerns who interact and remain in contact for mutual assistance or support). The definition of network offered by Houghton Mifflin (2000) implies that network nodes are specified at a single level of hierarchy. The term, *Functional Abstraction Network* (Elm, Roth, Potter, Gualtieri & Easter, 2005) appears to distort the concept of network.

COMMENTARY ON LIND'S CRITIQUE

Lind (2003) identified several issues, some of which he characterized as methodological and others as conceptual. Following the sequence used by Lind (2003), I will address the methodological issues before the conceptual issues.

Methodological Issues

In this section, I paraphrase the more significant of Lind's methodological issues as stated in his 2003 paper and offer my commentary. Note that my statement of the issues is not a quote but rather my summary of Lind's concern. My response to that concern is formatted as a bullet point.

Issue: There are no procedures or guidelines for knowledge acquisition.

- In a design effort, we need to acquire knowledge and then represent or summarize it in a form that can support design. As noted by Burns and Vicente (2001), the primary thrust of expositions of Cognitive Work Analysis has been on representation. This could be seen as neglectful but Cognitive Work Analysis is part of the larger enterprise of Cognitive Systems Engineering, which has a plethora of Knowledge Acquisition methods. Those who practice Cognitive Work Analysis select from those methods and, given the extensive treatment of those methods elsewhere, there seems little need to elaborate on them in expositions of Cognitive Work Analysis.

Issue: There is no process for building, revising, modifying and validating models.

- Processes for building, revising, modifying and validating models are always incomplete but Vicente has offered many details for Cognitive Work Analysis. His guidelines for constructing an Abstraction-Decomposition map are detailed (Vicente, 1999, pp 165-6). The processes and guidelines offered by Lind (1994, 1999b) for Multilevel Flow Modeling are no more explicit or extensive. In addition, some in our community continue to develop and extend guidelines for different stages of Cognitive Work Analysis (e.g., Naikar, Hopcroft & Moylan, 2005).

Issue: There are no convincing arguments for the number of means-end abstraction levels or part-whole levels. It is a strange coincidence that the number of levels along the two dimensions is the same.

- Pragmatically speaking, there are five levels of abstraction. The limits are anchored by the Why-What-How sequence. Purpose is the ultimate end and so represents the upper limit. Physical material represents the lower limit. Objects, functions, values and purposes are conceptually different and we further find it useful to distinguish physical functions from purpose-related functions. These distinctions should not be considered inviolate because identification of more appropriate distinctions is always possible, but they do seem to correspond to the way experts conceptualize their work. Note that this is a pragmatic issue (*the distinctions correspond to how experts think*) rather than a metaphysical one (*the distinctions do not reflect an inherent structure of the world*).

- Except in Lind's own papers, I have never seen a claim of five decomposition levels and it is definitely not a principle of the Abstraction-Decomposition analysis. Levels of decomposition are selected based on the knowledge acquisition protocols. Analysis extends to a level found useful for domain experts.

The inclusion of control systems in the Abstraction-Decomposition map is a controversial issue.

- Lind attributes the controversy to incompatible statements made by Vicente, Rasmussen, Sanderson and Miller. He takes Miller and Sanderson (2000) to task because they, in forwarding a claim that the Abstraction-Decomposition analysis cannot cope with biological systems, imply that process plants do not incorporate control systems. Miller (personal communication) has indicated that she and Sanderson had not meant to imply that, and she now believes that the term *entangled* is a better descriptor for the biological control systems problem.

- Lind takes Vicente (1999, p 9) to task because of Vicente's definition of a Work Domain as a *system being controlled, independent of any particular worker, automation, event, task, goal, or interface*. Lind takes this definition to mean that control systems should be excluded from an Abstraction-Decomposition analysis, but I take this definition more generally to mean that agency should be excluded from the analysis. Thus, control systems are not to be analyzed as causal loops within the Abstraction-Decomposition analysis. Control systems realize a function and that function—together with the appropriate decomposition—should be included in the Abstraction-Decomposition map, but the causal loop must be investigated through some other form of analysis.

- From my reading of Lind's papers, I understand that analysis of processes within a control system is the role he has set for Multilevel Flow Modeling. If that is the case, Multilevel Flow Modeling and Abstraction-Decomposition analysis do not compete for the same ground and my email exchanges with Lind suggest to me that he would agree. Burns and Vicente (2001) also argue that these two analyses yield different information.

Conceptual problems

Much of what concerns Lind in this section of his critique relates to semantics. In the first paragraph of this section he states, *the repository of concepts used to characterize the content of the five means-end levels is a major source of confusion* (Lind, 2003, p 73). This, indeed, is the single point he makes that I find telling. The confusion he expresses about the semantics that underpin Abstraction-Decomposition analysis is understandable. The Cognitive Engineers who practice Abstraction-Decomposition analysis are, unfortunately, inconsistent in their use of words. Vicente (1999) has made a systematic and disciplined attempt to clarify the semantics and his book remains the benchmark for defining relevant concepts.

As one might imagine, others do not always follow Vicente precisely. In itself, this is not problematic because we should expect that usage of concepts would evolve as we develop this technique, but many analysts depart from Vicente's terminology for no apparent reason, without explanation, and without acknowledging the departure. I am left with the impression that there is a troubling lack of discipline in our community regarding the meaning of terms and that relatively few are concerned by that state of affairs. For example, in response to my expression of concern regarding our casual use of words (Lintern, 2004), John Flach has argued that it is an issue of *which is to be the master* (Flach, 2004), presumably implying that we can use words in any way we desire.

I find this attitude as troubling as Lind (2003) apparently does. He notes our use of the term *function* and argues that we do not recognize its multiple meanings. The same can be said of the term *process* and it is a further concern that there is overlap in some of these meanings between the two terms. Nevertheless, Vicente (1999) defines *function* in the manner in which he intends it to be used in Work Domain Analysis, and—while he does not specifically define *process*—his definition of *product model* indicates what he means by *process* (Box 1). There is also confusion about the distinction between *purpose* and *goal,* but again Vicente defines the manner in which they can be distinguished (Box 2). Nevertheless, there are many examples in the literature of Abstraction-Decomposition analysis completed since the publication of Vicente's book in which *process* is equated to *function* and *goal* is substituted for *purpose*.

Box 1: Function & Process

Function - a goal-relevant structural property of a Work Domain. An Affordance that is relevant to the Purposes for which the Work Domain was designed (Vicente, 1999, p 6).

Product Model - a black-box Model describing the Behavior of a System but not the process or mechanism by which that Behavior is generated (i.e., "what", but not "how"). A Model of System Behavior rather than System Structure. (Vicente, 1999, p 7).

Comment:
By this definition of *function*, it is a structural property whereas the usage of *process* in this definition of Product Model treats it as an action property

Box 2: Purpose & Goal

Purposes - the overarching intentions that a Work Domain was designed to achieve. Note that Purposes are properties of Work Domains, not Actors, and that they are relatively permanent (unlike the Goals of Actors, which change over time) (Vicente, 1999, p 8).
Goal - a State to be achieved, or maintained, by an Actor at a particular time. Note that goals are attributes of Actors, not Work Domains, and that they are dynamic (unlike the Purposes for which a Work Domain is built, which are relatively permanent) (Vicente, 1999, p 6).

This lack of discipline in use of words is particularly troublesome for the practice of Abstraction-Decomposition analysis because this method generates so much controversy. Our continuing lack of discipline in this area can only serve to confuse those we are trying to inform and leave us open to the sort of criticism that Lind has leveled.

Many of the conceptual issues Lind identifies do not emanate from unclear and inconsistent use of terminology and I respond to those issues below in the same manner I responded to the methodological issues.

Issue: A means-ends relation has causal properties but the Abstraction-Decomposition analysis does not deal with causes.

- Vicente (1999, p 7) is unambiguous. He refers to the structural means available for achieving the ends (Box 3). This is consistent with the common language interpretation of the means test (Houghton Mifflin, 2000), which essentially asks whether you have the resources that will permit you to live without additional resources. Vicente's treatment of means-ends excludes any consideration of causality, which is not to claim causality is irrelevant but to claim that its analysis is undertaken elsewhere.

Box 3: Means-Ends Relation

Means-Ends Relation; the relationship between adjacent levels in a Means-Ends Hierarchy. The level below a given level describes the structural means that are available for achieving the level above. The level above a given level describes the ends (or Functions) that can be achieved by the level below (Vicente, 1999, p 7).

Issue: The combination of means-end(s) and causality concepts is inconsistent with the intrinsic logic of many-to-one mappings.

- A key benefit of the Abstraction-Decomposition map is that it reveals complex mappings; many-to-one, many-to-many and one-to-many. The standard Systems Engineering strategy of assigning Integrated Product Teams to different functional areas prevents mapping of subtle and unexpected interdependencies between functional areas. To my knowledge, the Abstraction-Decomposition map is the only representation available today that can reveal these interdependencies and it does so by virtue of allowing complex mappings. As noted above, means-ends relations are not causal. The incompatibility of causal concepts with complicated mappings is one reason that practitioners of Cognitive Work Analysis do not enter causal concepts into their Abstraction-Decomposition maps.

Issue: It is important to distinguish between different types of means-ends relations.

- Again, Vicente (1999, p 7) is unambiguous. There is one type of means-ends relation. Would others be useful and could they be incorporated into the Abstraction-Decomposition analysis? Resolution of that question would require extensive exploration but I doubt it would be a productive exercise. Lind (1999b) offers a number of means-ends relations for Multilevel Flow Modeling and they are possibly useful for the form of technical analysis he undertakes, but the distinctions he makes have no obvious implications for the design of Human-Systems Interaction.

Issue: The semantics of the means-ends and causal relations in the Abstraction-Decomposition map allows circular plant descriptions.

- The issue of circular description is one of the reasons given by Elm (2002) for the Functional Abstraction Network developed in Applied Cognitive Work Analysis as an alternative to the Abstraction-Decomposition map. It is possibly no accident that the Functional Abstraction Network developed by Elm et al (2005) has some of the characteristics of a Multilevel Flow Model, including references to causality (Elm, 2002). However, circular descriptions are not valid in an Abstraction-Decomposition map and those who note it as a problem do so because they do not understand the nature of means-ends relations as defined by Vicente—and do not recognize the significance of the complex mappings. Neither Multilevel Flow Modeling nor the Functional Abstraction Network of Applied Cognitive Work Analysis can depict functional interdependencies. That does not invalidate their use as tools for design of Human-Systems Integration but those tools do not substitute for an Abstraction-Decomposition map.

Issue: The inclusion of actions on the level of physical function in the Abstraction Hierarchy (Rasmussen et. al., 1994) is problematic. Most people would regard actions as genuine means (consider e.g. the following sentence "*the turning of the valve by 30 degrees is a means to increase the flow of water*") but actions does not to fit naturally in the same category as material objects like pumps and valves.

- I remain uncertain whether Lind meant to attribute that quote to Rasmussen et al., (1994) but I could not find it. Vicente (1999) is clear on the fact that action statements are not to be included in the Abstraction-Decomposition map and I—and at least some others—follow this guidance rigorously. In my view, Vicente's recommendation is consistent with the exposition of Rasmussen et al., (1994). It is an unfortunate characteristic of the English language that certain words can signify either functions or actions (e.g. landing as relevant to aircraft) and I sometimes notice words that have this characteristic in Rasmussen's and Vicente's expositions. I have not found Rasmussen to be as unambiguously explicit as Vicente but I do not find noteworthy conceptual incompatibilities in their respective treatments of Abstraction-Decomposition analysis. Lind's claim that actions do not to fit naturally in the same category as material objects is consistent with Vicente's position and, I believe, with Rasmussen's.

- The search for conceptual incompatibilities between Rasmussen and Vicente is nevertheless, an unfortunate exercise. We should hope that we are developing the tools of Cognitive Work Analysis and I doubt that anyone, including either Rasmussen or Vicente, would imagine that any of the earlier treatments are flawless. From that perspective, we would hope that the more recent expositions refine issues and correct inconsistencies.

Lind takes the view that confusion about semantics results from attempts to generalize to a number of work domains but I continue to believe that the potential to generalize across work domains is a major strength of the Abstraction-Decomposition analysis. Lind also takes the view that clarification of the semantics will restrict the range of domains to which the Abstraction-Decomposition analysis is applicable, while I take the view that clarification of the semantics will extend the range and value of application. These are unsupported claims but we should note that no research endeavor could progress without a number of strategic commitments of faith.

Some of Lind's critique is premature, but at some stage it is essential that the Abstraction-Decomposition analysis be shown to contribute to the design of cognitive systems. Some strong examples of success are already available and have been noted earlier in this paper. Work is ongoing and as that is reported in the public domain, we will be able to update our ideas about this form of analysis. However, I remain unaware of any competing analysis that is devoted exclusively to mapping out functional structure, and part of the disagreement may be about whether it is useful to map the functional structure. That may be a focus for future discussion; suffice to say at this stage that those who undertake Cognitive Work Analysis believe it important.

This problem of semantic clarification is an issue that we, as a community of practitioners, have not taken seriously and we could do well to use Lind's critique of conceptual problems as one guide in formulating an agenda. As I have noted however, there are several things that Lind says about semantics that would lead us in the wrong direction. Furthermore, he offers a number of remarks in the *Conceptual Problems* section of his paper that reveal a distorted understanding of the role and application of the Abstraction-Decomposition analysis. We need to sort through these remarks to identify those that make sense if we are to be guided rather than distracted by them.

MULTILEVEL FLOW MODELING

...the interaction between automated controls and their responses to operator intervention can only be understood fully if it is seen as a goal oriented activity. Lind, 1999, page 171

Lind (1999a; 2003) offers Multilevel Flow Modeling as a better strategy for dealing with functional abstraction, functional decomposition, and means-ends relations. The main objectives of Multilevel Flow Modeling are *to develop concepts and methods for modeling of complex industrial artifacts and to use the models in conceptual design of industrial automation systems, including intelligent controls and supervisory functions for the operator* (Lind, 2003, p 67). The strategy is to *represent goal structures and their relationship to underlying causal mechanisms of the plant in a formalized way* (Lind 1999b).

A tutorial example from Lind (1994) illustrates some of the basic concepts and the strategy. Figure G-2 depicts a system with two interacting feedback loops. Cold and hot inflows of fluid are mixed to produce an outflow at a preset temperature and flow rate. Feedback loops through S1-R1 to control valve V1 and S2-R2 to control valve V2 ensure that the system settles on a stable flow at the preset temperature.

The Multilevel Flow Model of Figure G-3 formally depicts the mass and energy flow structures involved in mixing of the two streams of water and the two feedback control functions involved in balancing the temperature and flow rate. Connections show how system functions are integrated to satisfy system goals. Connections identify means-ends relations, but in contrast to the Abstraction-Decomposition map as described by Vicente (1999), there are eight types of means-ends relations. One corresponds to the type used in the Abstraction-Decomposition map and another corresponds to a causal link.

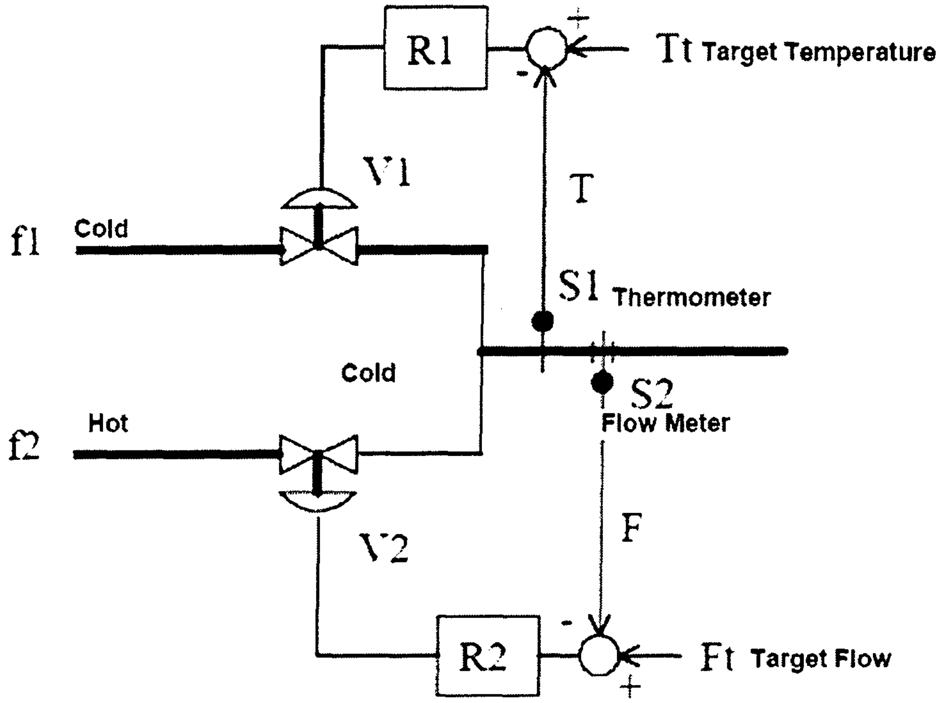

Figure G-2. A two-variable process with two feedback loops (Lind, 1994)

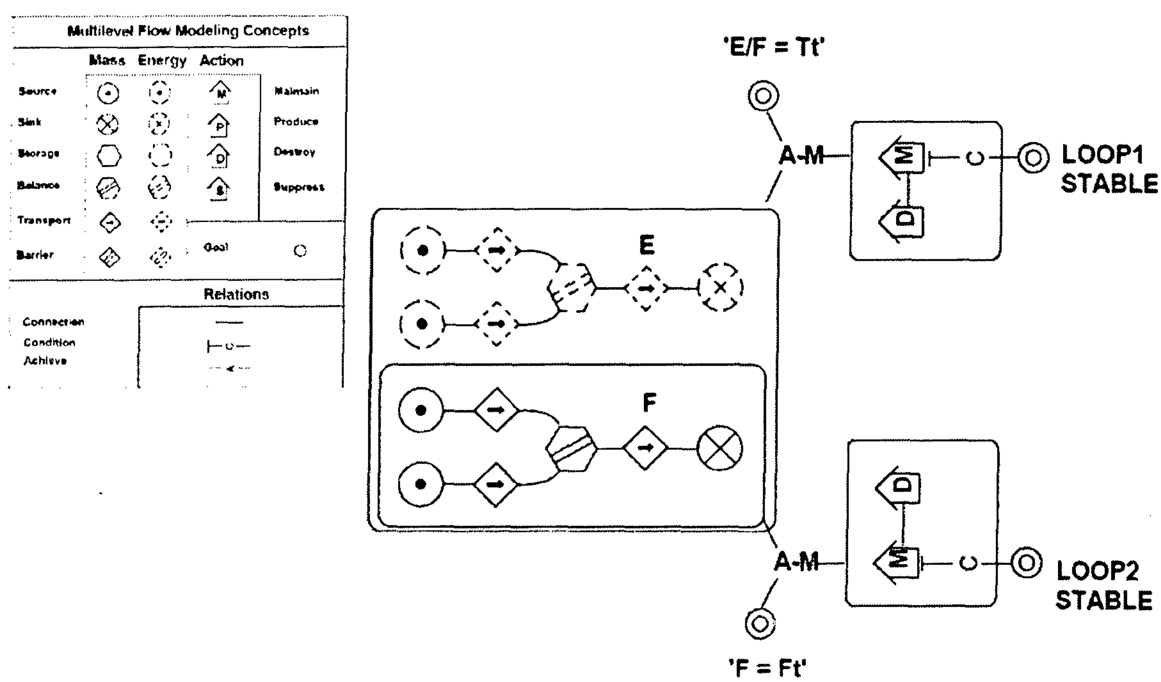

Figure G-3. A Multilevel Flow Model of the two-variable process, two-feedback loop system

The examples offered by Lind (1994, 1999b) are primarily technical and offer little in the way of socio-technical analysis. Unlike the Abstraction-Decomposition map, which is confined to a representation of structure, a Multilevel Flow Model represents both process and structure. Burns and Vicente (2001), in their contrast of Abstraction-Decomposition analysis to Multilevel Flow Modeling, concluded that the former produces a work domain structure model and the latter a work domain goal model. They note that different kinds of analyses yield different information. Thus, the choice of method should be determined in part by what sort of information is needed.

Burns and Vicente (2001)

The paper by Burns and Vicente (2001) offers another tutorial example on Multilevel Flow Modeling and also a detailed comparison of Multilevel Flow Models, Abstraction-Decomposition maps, and Decision Ladder representations. It is an evocative and succinct paper. I recommend it be read in full, but I provide a brief explanation of the ideas in that paper below.

The purpose of analysis is to abstract from specific details to provide a generic description. In Cognitive Engineering, that description should have implications for design. Vicente (1999) has argued that analysis can be of *tasks* or *work domains*. Task descriptions identify actions that can or should be performed by one or more agents. Work domain descriptions come in two forms; they identify either *structure* or *goals*.

A Multilevel Flow Model is of the goal type; it reveals how structures are connected to goals (desired states). The connections are causal links that can be characterized as goal–achievement relations. The description is not hierarchic; it allows circular descriptions of the form that would be needed to describe the information and energy flows within a closed loop system (e.g. a home heating system).

An Abstraction-Decomposition map is a work domain structure model; it does not include goals or actions. The purpose or functions of the work domain are connected via structural means–end relations to functions or objects at the next level down the hierarchy. Levels are connected in a Why-What-How relationship where entries at the next highest level show why a function or physical resource is in the work domain, and entries at the next lowest level identify the resources needed to realize a purpose or function (Figure G-4).

In comparison to a Multilevel Flow Model, the Abstraction-Decomposition map offers a description of purpose rather than goals. The description is hierarchic, moving from abstract at the top to concrete at the bottom. There are no circular loops between levels and each level offers a different kind of description. The structural means–ends relations are directional with ends ordered above means throughout.

A Multilevel Flow Model reveals states important to predefined modes of operation but does not reveal the purpose of the work domain. A Multilevel Flow Model indicates the roles that certain pieces of equipment play in achieving operational states. That could aid development of an equipment use procedure, but it would be a procedure that would be brittle in an unanticipated situation because it is based on event-dependent goals.

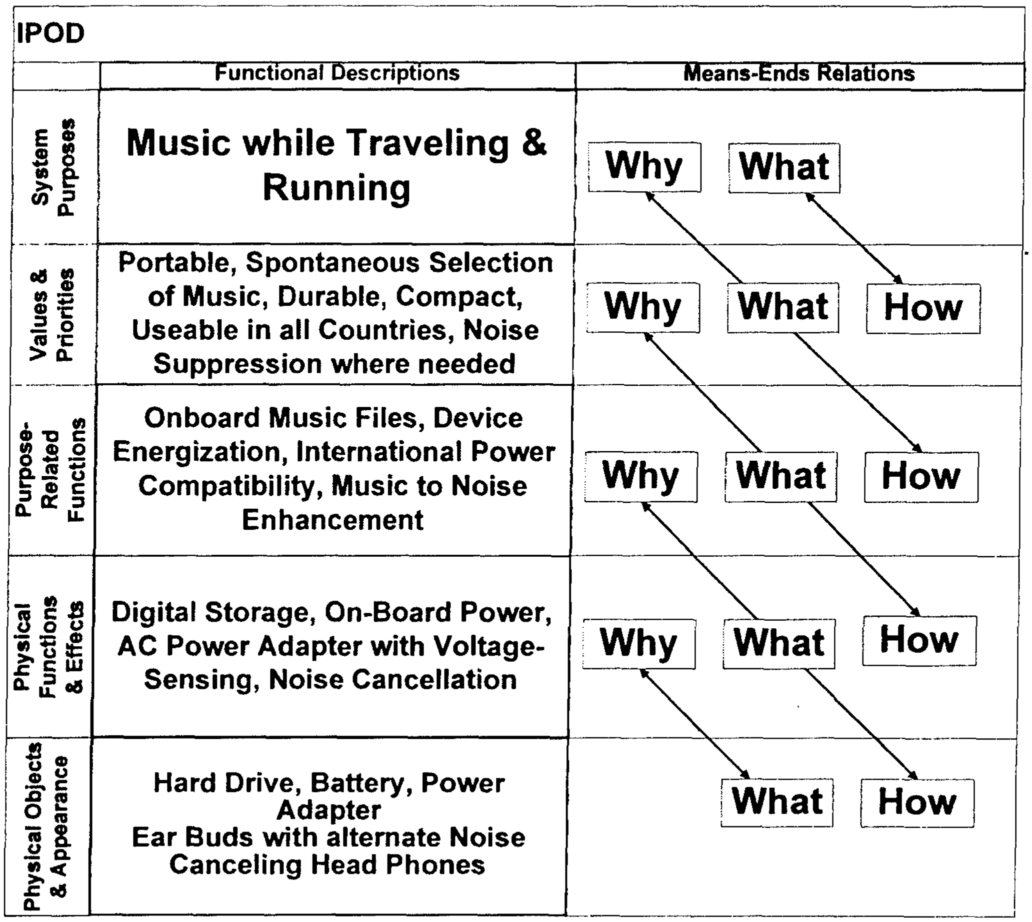

Figure G-4. An abstraction hierarchy for a portable music system (IPOD) showing the Why-What-How links for the means end relations.

The Abstraction-Decomposition analysis provides an event-independent description; it reveals how different material resources and their functions support system purpose. Action possibilities may be detected through an understanding of how equipment works, but specific courses of action, target goals, or equipment usage are not specified.

Cognitive Work Analysis distinguishes structural from task analyses. The task description of choice is the Decision Ladder. As in a Multilevel Flow Model, a Decision Ladder shows desired operational states and activity required to realize them but the two forms of description differ in content. A Multilevel Flow Model uses goal–achievement relations to connect desired operational states, while a Decision Ladder uses information links to depict a task as a sequence of desired operational states. The Decision Ladder offers a richer description of cognitive and action states by outlining information processing stages and cognitive shortcuts. Unlike an Abstraction-Decomposition map, the Decision Ladder has loops and cycles and is not hierarchic.

Functional Abstraction Network

I remain unclear regarding the strength of the connection between Applied Cognitive Work Analysis and Multilevel Flow Modeling, but similarities are evident. In particular, the

Functional Abstraction Network of Applied Cognitive Work Analysis bears a striking resemblance to a Multilevel Flow Model. Within the community of Applied Cognitive Work Analysis practice, the intellectual debt to both Rasmussen and Lind is acknowledged. However, presumably in reference to Abstraction-Decomposition, it is said that *the term "hierarchy" is actually a misnomer—the structure of the model is actually a NETWORK* (Elm, 2002). This claim is both distracting and misleading. The product of Applied Cognitive Work Analysis is a network but the product of Abstraction-Decomposition analysis is a hierarchy, albeit a two-dimensional hierarchy in which one of the dimensions (i.e. abstraction) does not conform to the common hierarchical property of containment.

SUMMARY

Lind's Critique

I am troubled by the tone of Lind's critique; it is predominantly negative and, while offering some useful observations, does so in a tone that is unlikely to encourage those of us working on Abstraction-Decomposition analysis to take him seriously. Unfortunately, the content of Lind's critique has more weaknesses than the does the method he critiques. He argued as if the issues he was dealing with constituted fatal flaws, but—even if valid—most of the issues he raised did not point towards fatal flaws but rather towards issues that could be resolved and, if resolved, would strengthen the method.

The Cognitive Engineering community is a relatively small group of analysts and designers who are tackling difficult problems in different ways. No one has yet established an approach that is undeniably effective with the full range of problems that we face. Indeed, subtleties of the methods we use are difficult to grasp and one needs to work extensively with any one of them to gain any significant level of appreciation of its value. As is true of many analytic methods, it is unlikely that a well-founded critique of such a complex method as Abstraction-Decomposition analysis could come from someone who has not worked extensively with it. While Lind has offered a number of useful observations, we should be selective about which of them we take seriously. Any attempt to deal with those based on misunderstandings would create more confusion without adding value.

I recognize that Lind was involved in early developments of Abstraction-Decomposition analysis, but his misconceptions especially about the purpose and nature of abstraction and means-ends relations are significant. I wonder at this but speculate that he has not kept abreast of developments over the past 15 years or so. In my own view, the early work as reported by Rasmussen (1986) on what might be termed the Risø analysis[12], was fragmented and partially inconsistent with the later developments reported in Rasmussen et al (1994) and Vicente (1999). The 1986 book is radical, evocative, and sometimes inspirational, but the ideas it contains have been refined considerably since its publication. I suspect that Lind has not maintained familiarity with these developments.

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[12] After the Risø National Laboratory at which Rasmussen served as a professor of Cognitive Systems Engineering.

It should also be noted that Rasmussen typically takes a global perspective, emphasizing cognitive systems (e.g., Rasmussen, et al., 1994) while Lind focuses on automated control systems. On several occasions, while reviewing Lind's papers, I puzzled over the origin of certain statements and have come to believe that they emerge from Lind's techno-centric view and his focus on automated control systems. That, however, does not make him wrong; the substantive content of his claims need to be assessed and I have sought to do that in this commentary.

Abstraction-Decomposition Analysis

Abstraction-Decomposition analysis has a unique role to play. To my knowledge, no other analytic method lays out functional structure in a manner that supports formative design of complex socio-technical systems. I have yet to find anything comparable in Systems Engineering. Only Gibson (1979) and Rand (1979/1990) promote a similar view and they do not propose any explicit means of representing the spaces they conceptualize.

The practice of Cognitive Work Analysis is occasionally criticized for its emphasis on Work Domain Analysis—that often being the only phase of Cognitive Work Analysis that is completed. In their recent book, Burns and Hajdukiewicz (2004) ignore the remaining four phases of Cognitive Work Analysis on their way to developing an approach to Ecological Interface Design. While this emphasis might be seen as a weakness, it has resulted in the relative maturation of Work Domain Analysis and its analytic product, the Abstraction-Decomposition map.

Abstraction is a challenging concept. The potential contribution of the abstraction dimension may be little appreciated because it is poorly understood and is readily confused with decomposition. Sarcedoti (1974) is one who, in proposing a hierarchy of abstraction spaces as a means of reducing combinatorial complexity for planning, appears at first to appreciate the contribution of an abstraction analysis. However, having outlined this proposition, Sarcedoti then proceeds to treat abstraction in terms of decomposition. I suggest that the distinction between abstraction and decomposition, although logical, is not obvious and those who analyze complex socio-technical systems will not turn their attention to it unless they are encouraged to do so. This is possibly a formative contribution that those who are developing the Abstraction-Decomposition analysis can make to Cognitive Engineering practice.

A Personal View of Rasmussen's Contribution

Rasmussen's most important foundational assumption relates to the primacy of structural analysis of the workspace. In that regard his is an ecological approach (Gibson, 1979) in which structural analysis of the environment is central. Most cognitive analysis deals with processes, tasks, or activities. Rasmussen's approach does not deny the value of process, task, or activity analysis but proposes that the structural analysis is essential.

A further important foundational assumption is that the design of a cognitive workspace must be structured to be compatible with effective patterns of cognitive work (e.g., problem solving, planning) and Rasmussen proposed that a functional abstraction-decomposition space captures the essential properties of that workspace. Those who do not care for the abstraction-decomposition structure must reject this foundational assumption of compatibility with the pattern of human work, or else propose alternative dimensions for the workspace structure.

It should be noted that the abstraction-decomposition space is a construction abstracted from descriptions of cognitive activity. It is not a metaphysical statement about the nature of the world but rather a pragmatic statement about how we believe experts perceive their cognitive workspace. As with any analysis, it emphasizes certain properties at the expense of others. It remains possible that different dimensions would map the structure of cognitive work more accurately. We might also wonder whether different types of links (e.g., if-then relationships, Anne Miller, personal communication) would capture reasoning processes more accurately. Any such speculations would have to be evaluated against a suitable body of data and it is also possible that the structure of cognitive work is not generic across different work domains. Progress of that sort would not, however, invalidate Rasmussen's foundational assumptions but would rather validate his structural assumption and his reliance for specific insights on descriptions of expert cognitive activity.

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APPENDIX H. DR. CUMMINGS' CRITIQUE OF "FORMS OF REPRESENTATION FOR COGNITIVE DEMANDS IN SYSTEM ACQUISITION"

Background

Dr. Mary (Missy) Cummings developed this critique of "Forms of Representation for Cognitive Demands in System Acquisition" for Dr. Lintern under a subcontract to General Dynamics. Dr. Cummings is a professor in the Massachusetts Institute of Technology's Aeronautics & Astronautics Department. Her research approach has been shaped by her extensive military experience and her experience as a pilot of one of the Navy's most advanced fighter aircraft. She has a strong interest in the use of cognitive engineering methods in the design of complex military systems.

The document that she critiqued, "Forms of Representation for Cognitive Demands in System Acquisition" was actually the proposal that Dr. Lintern submitted to AFRL/HECS for this effort. Dr. Cummings sometimes refers to the document as the "proposal" in this appendix.

Executive Summary

The following report analyzes Cognitive Work Analysis (CWA), with special emphasis on command and control decision support systems. Specific areas of investigation include problematic definitions and classifications associated with CWA, the incompatibilities of CWA with current systems engineering practices to include requirements generations, and limitations of CWA to include 1) embedded system representation, 2) application to intentional domains, 3) adaptation to revolutionary systems, and 4) ill-defined phases of analysis. A section is included to discuss current time critical targeting issues and the report concludes with a list of recommendations for future exploration.

1.0 Definitions

This report begins with a discussion of definitions. While it may seem a trivial and semantic discussion to reexamine definitions surrounding Cognitive Work Analysis (CWA) and the abstraction hierarchy and decomposition, these basic definitions are essential to their uses and applications. Before developing any further modifications or applications of these tools, their fundamental assumptions and theory must be addressed so as to not add any additions to a house of cards.

The first definition that requires analysis is that of the nature of CWA, which is advertised as a "formative" design approach as compared to descriptive (designs based on descriptive models) or normative (designs based on prescriptive models). Formative models are defined as "A model that describes requirements that must be satisfied so that a System (sic) could behave in a new, desired way (Vicente, 1999)." This definition is problematic because models do not "describe" requirements. Models generalize interrelations from observed and/or simulated data, ultimately to predict endogenous variables as a function of exogenous variables. While there are many different ways to model (words, mathematics, diagrams, etc.), tractable models can only represent interrelations of a small set of variables, and thus the usefulness of a model is typically inversely proportional to the number of variables (Sheridan, 2005). Since models are general and abstract representations, at best models can aid an engineer in developing requirements. Models do not map directly onto the development of requirements, especially detailed.

In addition, abstraction decompositions and hierarchies are not models. These are representations of system elements and architectures, but they fundamentally lack the ability to predict one or more exogenous variables. Jens Rasmussen, the originator of these tools, classifies them as a "framework for analysis and representation aimed at eliminating degrees of freedom in the set of behavior-shaping constraints...[which allows] converging on action alternatives (Rasmussen, Pejtersen, & Goodstein, 1994)." He further refers to the abstraction decomposition, a means-ends/part-whole representation, as a map for understanding how, what, and why a system is used.

The use of the abstraction decomposition/hierarchy to represent and map systems has been used extensively with varying degrees of success, but arguably it can be helpful in aiding designers attempting to understand a complex system. However, a map representation is not the same as a model, and both engineers and psychologists should be more careful in applying terminology that is not appropriate. Because abstraction decompositions are the backbone of CWA, it is not a modeling tool, but rather is a domain analysis and potential system architecture mapping tool which will be discussed below. Again, this discussion is not meant to trivialize the use of these tools as they can be helpful but calling them models is simply incorrect and misleading.

Lastly, a discussion on the term "formative" is warranted. CWA, as a formative approach to design, is supposed to describe requirements that MUST be met so that a system can behave in some predetermined, more effective manner. First, it is not at all clear how this definition is so different from normative since it is prescriptive as well (MUST). In addition, this definition further assumes that CWA analysts know what the "new, desired way" is. This problem is not one of semantics, especially for command and control systems. The operation of a nuclear power plant whose goal states are relatively time-invariant with low uncertainty (e.g., make required power safely) is quite different from that of a command and control network in which the operations are not only highly time-dependent, but also subject to large uncertainty, incomplete knowledge states, and changing goals. Any analysis approach that must have a defined "new, desired way" in order to generate requirements cannot be effectively applied to command and control systems.

2.0 Requirements

Any single analysis approach that guarantees comprehensive requirements is dangerous. Requirements generation is a research field in and of itself (now known as requirements engineering), with established journals, tools, and conferences. It is not a simple process and cannot be adequately addressed either by a single tool or a single designer or group of designers/engineers. Standard requirements practice contends that there are three types of system requirements: 1) functional (what the equipment must do), 2) nonfunctional (performance measures), and 3) constraints (the system limits.) In addition, it has been proposed that two categories be added, that of human performance and process requirements (Harrison & Forster, 2003). Other human factors practitioners have developed specific methodologies for requirements generation (Kirwan & Ainsworth, 1992; Laughery, 1999; Potter, Elm, Roth, Gualtieri, & Easter, 2002; Riley, 1992), with varying degrees of success, and there has not been a generally accepted approach for cognitive requirements generation within the larger context of systems engineering.

It has been asserted that CWA can generate (or describe) human systems requirements, however, this is a point of debate. For example, in one case study, use of the CWA provided the following functional requirements for a training system (Sanderson, 2003):

- Design Objectives: training system must be designed to satisfy the training objectives of the work domain
- Data Collection: training system must be capable of collecting data related to measures of performance
- Scenario Generation: training system must be capable of generating scenarios for practicing basic training functions
- Physical Functionality: training systems must simulate the functionality of physical devices and significant environmental conditions
- Physical Attributes: training system must recreate functionally-relevant properties of physical devices and significant features of the environment

These functional requirements as generated by the CWA are not functional requirements as requirements engineers would term them so clearly there is a disconnect. It has been asserted that CWA tools can aid in the generation of "information requirements" (Miller & Vicente, 2001; Potter, Gualtieri, & Elm, 2002; Vicente, 1999), but it has yet to be established how and when information requirements can be inserted into the more comprehensive systems requirements process. Moreover, it has been shown that CWA cannot be used to generate comprehensive requirements for revolutionary intentional domain systems[13] (Cummings, 2003). In addition, as will be discussed in a subsequent section, it is not clear whether or not CWA should be used for intentional domains that are time-dependent with high degrees of uncertainty such as what occurs in command and control systems.

3.0 CWA and Systems Engineering

Systems engineering is not a mutually exclusive task that belongs just to "systems engineers." The systems engineering approach recognizes that to successfully build and operationally deploy a system (such as a UAV, a ship, or even a command and control network , which is really a system of systems) a principled approach must be taken such that all the different components of the system are seamlessly integrated in final design stages to meet customer requirements. The job of integrating the sub-systems does not fall just to systems engineers (who are often system analysts) and program managers, but also to any engineer of any background who will integrate his/her system with one or more additional systems.

[13] An intentional domain is one in which human intentions constrain the systems such as in command and control systems, versus a "causal domain" in which physical laws of nature constrain the system.

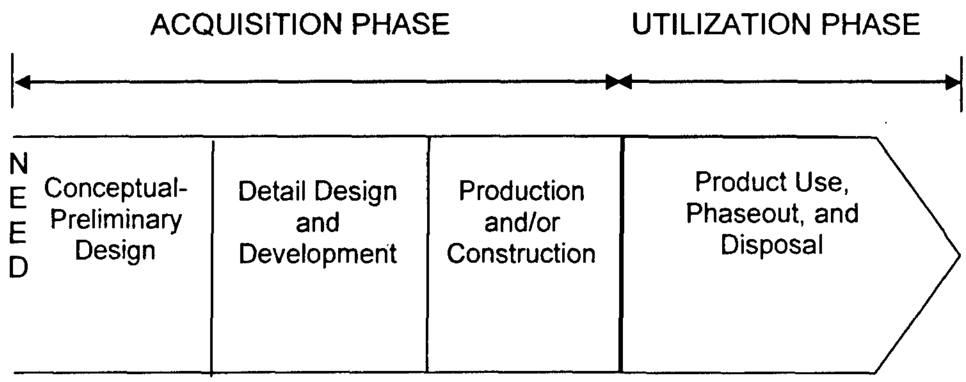

Figure H-1: The Waterfall Systems Engineering Approach

By the very nature of cognitive engineering, all cognitive engineers should be "system engineers" in that the human component is always integrated with multiple layers of the system. The primary purpose of a cognitive engineer is not to ensure the system supports the human, but that the human is effectively integrated into the system such that overall operational success can be achieved.

In the past, military systems acquisition typically followed a waterfall type of approach as seen in Figure H-1 (Blanchard & Fabrycky, 1998). However, recent advances in systems engineering approaches, suggest that a more concurrent approach is needed both for a leaner, more cost-effective process as well as mitigation of risk. This approach to systems engineering is known as

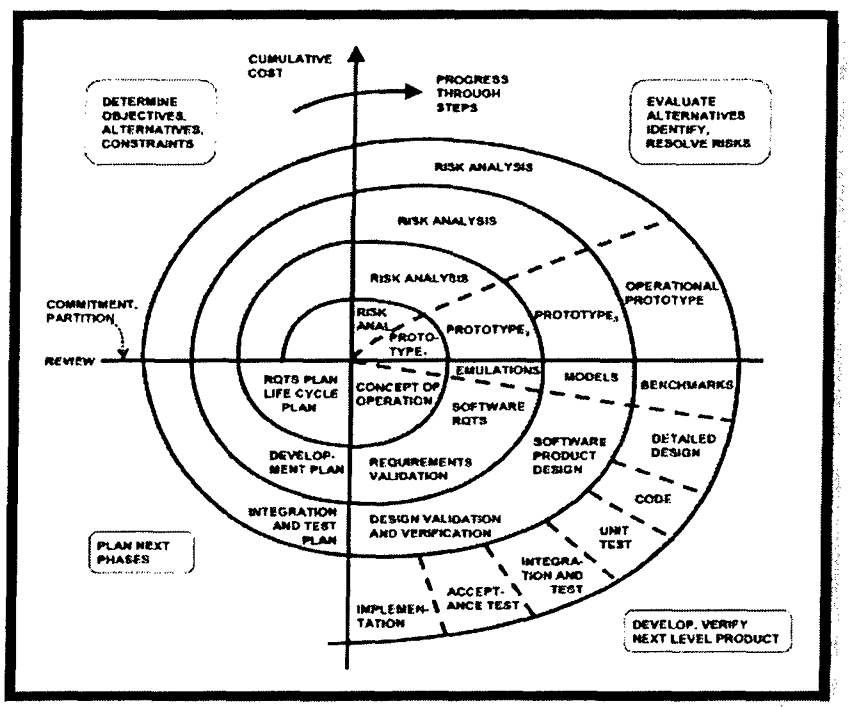

Figure H-2: The Spiral Systems Engineering Approach

the Spiral Model (Figure H-2, (Boehm, 1988)) and has replaced the waterfall model in most large system design and development projects.

While CWA takes a systems-theoretic approach in potentially determining cognitive requirements only after the larger system is mapped, it is not a systems engineering approach, cognitive or otherwise. Regardless of which systems engineering model is used, in addition to the model in Figure H-2 and the need for requirements generation, key elements of systems engineering include concept exploration, demonstration and validation, system integration, cost-benefit analyses, and design and development (Smootz, 2003). CWA does not address any of these areas. The major drawbacks to CWA are 1) no definitive link to design (and have been routinely criticized for such), 2) a lack of testing and verification leverage points, and other than showing vague links to other potential supra and subsystems, 3) no information is given towards effective integration strategies.

In terms of a real systems engineering model, as it stands now with its five phases, CWA is at best an analysis tool for human systems integration information requirements. In addition to other tools such as legitimate models, computer simulations, and more traditional cognitive task analyses, CWA can aid in identification of requirements for human-system interaction. This is not a trivial statement. If CWA can be shown to reliably and clearly delineate those information requirements for what, how much, and when human interaction is needed in a system, it could revolutionize the human systems engineering process.

4.0 CWA Limitations

At the very heart of the CWA methodology is the use of the abstraction-decomposition matrix and well as abstraction hierarchies (a form of means-ends analysis). These tools in theory represent system structure at different levels of abstraction so that a system's functions can be decomposed into sub-systems. This function decomposition is not new to the field of systems engineering and in fact, under different names, has been in use much longer than CWA has been in existence. The following quote is from the most established systems engineering text in existence.

"Functional analysis is the process of translating system requirements into detailed design criteria, along with the identification of specific resources requirements at the subsystem level and below. One starts with an abstraction of the needs of the customer and works down to identify the requirements for hardware, software, people, facilities, data, or combinations thereof (Blanchard & Fabrycky, 1998)."

4.1 Problems with Embedded Control Loops

However, where CWA differs from typical system engineering functional decompositions is the CWA assertion that its decompositions represent the system structure independent of any human, automation, event, or task goal. A significant drawback to this approach is that embedded control systems cannot be represented in the CWA abstraction decomposition and this causes the subsequent representation to be both artificial and likely incorrect. While current criticism of the CWA flaw has been directed towards its application to process control (Lind, 2003, 2004), this is a criticism that is even more applicable in the command and control domain. There are countless embedded control loops found at all levels of C2 such as autopilot in planes, GPS navigation, electronic intelligence, radar-tracking solutions for fire-support, etc. Military platforms and C2 networks cannot exist without embedded control loops and with network-centric warfare on the immediate horizon, the presence of embedded control loops will only increase.

4.2 Adaptation to Revolutionary Systems

While advertised as a way to design revolutionary decision support systems, CWA can only be applied to existing systems (Cummings & Guerlain, 2003). CWA assumes an existing organizational structure, existing infrastructure, existing users, and clearly defined boundaries. For decision support systems in revolutionary systems, CWA cannot be effectively used without other cognitive task analysis methodologies such as cognitive walkthroughs and simulations.

4.3 Problems with Intentional Domains

CWA has been shown to be effective for analyzing the human role in causal systems such as process control (Vicente, 1999), but it's usefulness in intentional domains has been questioned (Cummings, 2003; Wong, Sallis, & O'Hare, 1998). Especially critical to command and control domains, the cause-and-effect relationships due to unanticipated events cannot be traced via the structural invariants provided by CWA. In addition, as mentioned previously, CWA has serious difficulty in addressing the concept of time in systems operations. In the first phase of abstraction decomposition, the analyst spends a great deal of time mapping out what, how, and why relationships. While this may be effective for causal systems whose operations do not change dramatically over time, this is a limitation of CWA that makes its application to command and control (intentional) systems extremely limited, as is the inability of CWA to incorporate cause-and-effect tracings for unanticipated events in intentional domains. Any functional or design requirement that comes from a CWA analysis for a command and control system should be suspect since there is no principled way within the analysis to address the critical time constraints.

4.4 Ill-defined Phases of Analysis

CWA is a laborious process and the last three of its five phases are very vaguely defined. Indeed, many researchers and analysts will only complete the first two phases and call their results a CWA. Specifically the analysis of strategies, social, organizational, and cooperation analysis, and worker competencies phases do not have similar principled tools that are used in the domain and control task analysis phases. Despite numerous tools that could be applied to these areas (social network theory, social judgment theory, decision trees, macrocognition, human performance modeling, etc.), it is not clear how and if these phases can provide any real contribution to the analysis of a system and the generation of any meaningful requirements for decision support.

5.0 Structure vs. Process

In the proposal there is a desire to separate structure and process. For causal systems this may be possible but for C2 systems which are inherently process driven this may not be possible. In the proposal, structure is defined as the instantiation of physical resources in a workspace. In C2 the overarching purpose of the system is to move the structure as the environment dictates. C2 is fundamentally a process and this may be yet another reason why CWA is not applicable to C2. Even Rasmussen warns that functional decomposition according to structural elements cannot occur because of human adaptation (Rasmussen et al., 1994).

Perhaps the distinction should be made between structure of decision support interfaces as opposed to physical resources. For example, how an interface is laid out can be structure and the processes are the functionalities supported such as communications, health and status monitoring, introducing new targets etc. In this case structure should be guided by basic cognitive and usability principles in conjunction with an understanding of process outcomes and goals. Unfortunately at this low level, CWA is not as useful as cognitive tasks analysis tools.

6.0 Conclusions

CWA as it stands now seems to be an effective tool for designers who need to develop abstract representation or maps of a complex system. One potential CWA application that is not addressed explicitly is that indeed the main strength of CWA may be to help designers elicit knowledge from subject matter experts. This is not a trivial benefit. It is often very difficult for cognitive engineers to grasp all the nuances of human interaction in complex systems so if the CWA methodology aids the practitioner in both identifying critical relationships and mapping them in relation to other systems, then this is a valuable tool. However, caution must be taken in that such linear two-dimensional representations can cause researchers to miss critical relationships (a hammer looking for a nail).

While CWA has merit in some areas, this report has identified four major problem areas in the application of the CWA methodology to command and control systems: 1) embedded system representation, 2) application to intentional domains, 3) adaptation to revolutionary systems, and 4) ill-defined phases of analysis. In addition, the disconnect between CWA and systems engineering was discussed and is particularly problematic in translating any information requirements to established functional and design requirements, within the larger systems engineering process.

The following recommendations highlight specific areas of potential exploration:

- Formalizing a human systems integration requirements generation tool that could include CWA or elements thereof.
- Significantly more research is needed in better defining the last three phases of CWA and demonstrating how they add overall value to the requirements process.
- Development of a more principled application of CWA as a knowledge elicitation and representation tool.
- Formalize a methodology in which CWA can be shown to provide consistent information requirements that can translate to display design.

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APPENDIX I. DR. KUGLER'S COMMENTARY ON DR. CUMMINGS' CRITIQUE[14]

[14] See Appendix H.

BACKGROUND

Dr. Peter Kugler developed this commentary on Dr. Missy Cummings' critique of "Forms of Representation for Cognitive Demands in System Acquisition" (Appendix H) for Dr. Lintern under a subcontract to General Dynamics. Dr. Kugler is a private consultant with extensive experience in the foundations of cognitive science, computer science, and artificial intelligence. He is a Visiting Professor at the University of Connecticut's Center for Ecological Psychology. In recent years, he has turned his attention to the foundational issues of cognitive engineering as it has become evident that the challenges faced by cognitive engineers parallel those faced by cognitive scientists.

DISCUSSION

There are a number of comments that I want to make on a number of different levels.

1. First, I am struck by the difference in the way I think from the way Missy thinks. For me, first and foremost, is the issue of "how things work" (Box 1). This does not necessarily require an explicit statement about how things work but rather it typically appears implicitly in the manner of posing questions and guiding discussions. Posing questions can be as important (or more important) then answering questions. I do not see any new question being posed by Missy. When she poses a question it is about the appropriateness of Cognitive Work Analysis (CWA) rather than about 'nature' or about the design of a complex 'socio-technological system.'

Box 1: Questions about How things work

Regardless of how complex a system is, I have a fundamental belief that there is a way to inquire and talk about 'how this system works' in terms of fundamental design principles (versus analysis methodologies)—we may not know the principles but our goal is to discover them and to learn how to use them in the service of better and safer engineering designs. I want to know how the system is constrained and what classes of constraints are used. I want to know what provides an informational basis for system control and how this information is measured. I want to know how rigidly designed the measurement interface is and if there are there any regions in the control system requiring an 'open measurement interface,' e.g. a human observer, for 'out-of'-the-box' solutions to potential (or unforeseen) control situations. I also want to know how the human controller solves the control problem in these out-of-the-box control regions. Jens Rasmussen's CWA methodology was directed precisely at this last question but also touches upon many of the earlier questions (Rasmussen et al., 1994).

2. CWA is a methodological tool that can help organize the multitude of structural and functional descriptions that populate complex socio-technological systems. CWA is not a 'model' in the traditional sense. When Kim Vicente (1999) uses the word 'model' in the context of his discussion of formative, descriptive and normative models, the context makes it clear that the word 'model' refers to a more general class of models than the limited class of 'computable models,' including those referred to by Sheridan (2005) that involve explicit scaling relations between exogenous and endogenous variables. At this point (of reference) in Kim V's book the CWA is meant to provide a qualitative mapping (with some embedded quantitative relations

within certain cells) that is similar to the mapping that a menu provides with reference to food served in a restaurant. It is not clear if Missy wants a model to be predictive in the sense that scaling relations are both computable and predictive—my view on this issue is that most intentional systems are non-computable and we must consider the criterion of conventional prediction carefully before we pose it as a requirement. That requirement might in fact eliminate "life itself" as a class of phenomenon that would come under the umbrella of the criterion. I think Jens [Rasmussen] was well aware of this possibility and that is why he did not require this strong form of prediction as a requirement of his methodology.

3. The use of CWA is further confused when Missy suggests that it is inappropriate for 'intentional command and control systems' because there is too much incomplete knowledge, too much uncertainty, and too many changes in goal states. The original purpose of CWA was to help to understand how operators control a system when they depart from the designed control region, i.e. when they encounter an 'out-of-the-box' regime. It is precisely this out-of-the-box region that has the same 'intentional system characteristics' that Missy refers to with her term 'intentional control systems.' I agree that her command-control 'dog fighting' between pilots is a control system that has much more 'openness' in terms of observables and 'goal-purpose' but both of these solutions involve out-of-the-box engineering solutions. Moreover, these types of intentional situations lack the very sense of prediction that Missy critiques with reference to Kim's use of 'formative model.'

4. An additional recurrent concern of Missy's is how CWA relates to 'Requirements Engineering,' more specifically how it is deficient relative to the standards of 'requirements engineering.' She presents the area of 'requirements engineering' as an authoritative information source, when in fact it suffers from the same lack of clarity that all discussions do when the topic has to do with the topic of 'functionality' (or 'meaning'). I do not think it would be very difficult for me to talk to a 'requirements engineer' very long about the problem of how to define 'functionality' or 'meaning' before they would agree that their science is no better or more precise than the usage being advanced in CWA. In fact, I think the means-end analysis attempts to address this issue directly—I applaud CWA analysts for this direct attempt. But this is an area where I have been trying to drive the conceptual wedge concerning the problem of 'context-sensitivity' relative to functionality or meaning. I believe, in fact, that the work that you [Dr. Lintern] and I have been doing on this issue far surpasses anything I have seen in design engineering.

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APPENDIX J. DR. LINTERN'S COMMENTARY ON DR. CUMMINGS' CRITIQUE[15]

[15] See Appendix H.

Background

Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defense Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering. Dr. Lintern reproduces Dr. Missy Cummings' critique from Appendix H below, interspersed with his commentary (underlined italic font) at relevant points.

Executive Summary

The following report analyzes Cognitive Work Analysis (CWA), with special emphasis on command and control decision support systems. Specific areas of investigation include problematic definitions and classifications associated with CWA, the incompatibilities of CWA with current systems engineering practices to include requirements generations, and limitations of CWA to include 1) embedded system representation, 2) application to intentional domains, 3) adaptation to revolutionary systems, and 4) ill-defined phases of analysis. A section is included to discuss current time critical targeting issues and the report concludes with a list of recommendations for future exploration.

1.0 Definitions

This report begins with a discussion of definitions. While it may seem a trivial and semantic discussion to reexamine definitions surrounding Cognitive Work Analysis (CWA) and the abstraction hierarchy and decomposition, these basic definitions are essential to their uses and applications. Before developing any further modifications or applications of these tools, their fundamental assumptions and theory must be addressed so as to not add any additions to a house of cards.

The first definition that requires analysis is that of the nature of CWA, which is advertised as a "formative" design approach as compared to descriptive (designs based on descriptive models) or normative (designs based on prescriptive models). Formative models are defined as "A model that describes requirements that must be satisfied so that a System (sic) could behave in a new, desired way (Vicente, 1999)." This definition is problematic because models do not "describe" requirements. Models generalize interrelations from observed and/or simulated data, ultimately to predict endogenous variables as a function of exogenous variables. While there are many different ways to model (words, mathematics, diagrams, etc.), tractable models can only represent interrelations of a small set of variables, and thus the usefulness of a model is typically inversely proportional to the number of variables (Sheridan, 2005). Since models are general and abstract representations, at best models can aid an engineer in developing requirements. Models do not map directly onto the development of requirements, especially detailed.

<u>*I also do not like this definition of formative. I do not even think it captures the essence of Kim's discussion. My definition of Formative: to form or fashion from first principles. In Cognitive Work Analysis, formative implies a fashioning on the basis of the structure of the work system, such as the functional requirements as identified through the analyses.*</u>

In addition, abstraction decompositions and hierarchies are not models. These are representations of system elements and architectures, but they fundamentally lack the ability to predict one or more exogenous variables. Jens Rasmussen, the originator of these tools, classifies them as a "framework for analysis and representation aimed at eliminating degrees of freedom in the set of behavior-shaping constraints...[which allows] converging on action alternatives (Rasmussen, Pejtersen, & Goodstein, 1994)." He further refers to the abstraction decomposition, a means-ends/part-whole representation, as a map for understanding how, what, and why a system is used.

The use of the abstraction decomposition/hierarchy to represent and map systems has been used extensively with varying degrees of success, but arguably it can be helpful in aiding designers attempting to understand a complex system. However, a map representation is not the same as a model, and both engineers and psychologists should be more careful in applying terminology that is not appropriate. Because abstraction decompositions are the backbone of CWA, it is not a modeling tool, but rather is a domain analysis and potential system architecture mapping tool which will be discussed below. Again, this discussion is not meant to trivialize the use of these tools as they can be helpful but calling them models is simply incorrect and misleading.

I agree that the use of model in cognitive work analysis is undisciplined—unfortunately, this misuse of the term 'model' is pervasive in behavioral science.

Lastly, a discussion on the term "formative" is warranted. CWA, as a formative approach to design, is supposed to describe requirements that MUST be met so that a system can behave in some predetermined, more effective manner. First, it is not at all clear how this definition is so different from normative since it is prescriptive as well (MUST). In addition, this definition further assumes that CWA analysts know what the "new, desired way" is. This problem is not one of semantics, especially for command and control systems. The operation of a nuclear power plant whose goal states are relatively time-invariant with low uncertainty (e.g., make required power safely) is quite different from that of a command and control network in which the operations are not only highly time-dependent, but also subject to large uncertainty, incomplete knowledge states, and changing goals. Any analysis approach that must have a defined "new, desired way" in order to generate requirements cannot be effectively applied to command and control systems.

I cannot agree with this—normative and formative are definitely different and lead to different design solutions. Nevertheless, this disagreement may be based on the definition. Possibly, upon seeing my definition she may agree that there is a difference between formative and normative.

2.0 Requirements

Any single analysis approach that guarantees comprehensive requirements is dangerous. *Systems engineering appears to make this claim and surely this is essential, is it not?* Requirements generation is a research field in and of itself (now known as requirements engineering), with established journals, tools, and conferences. It is not a simple process and cannot be adequately addressed either by a single tool or a single designer or group of designers/engineers. Standard requirements practice contends that there are three types of system requirements: 1) functional (what the equipment must do), 2) nonfunctional (performance measures), and 3) constraints (the system limits.) *I actually do not see much of a difference between Missy's items 1) and 3)—I think of functionality and constraint as a duality.* In addition, it has been proposed that two categories be added, that of human performance and process requirements (Harrison & Forster, 2003). *Certainly yes to process requirements but human performance issues should also be assessed in terms of functionality/constraints and process requirements and also performance measures. In my view there is a troubling attitude in the engineering and design community—there is a tendency to believe that human functionality can be comfortably replaced with technological functionality coupled with the belief that human agents should be assessed in unique ways. I believe just the opposite, that human agents should be assessed on the same types of criteria but that human agents have the capacity for functionality that cannot be instantiated by technological means—and it is our early hard-core engineers and designers who seem to fall into this trap but cognitive engineers often seem to as well.* Other human factors practitioners have developed specific methodologies for requirements generation (Kirwan & Ainsworth, 1992; Laughery, 1999; Potter, Elm, Roth, Gualtieri, & Easter, 2002; Riley, 1992), with varying degrees of success, and there has not been a generally accepted approach for cognitive requirements generation within the larger context of systems engineering. *I am well aware of the work by Laughery and by Potter, et al. and, in my opinion, their statements on cognitive requirements generation are entirely unsatisfactory. In contrast, I do believe I have done a much better job in the work on Intelligence Preparation of the Battlespace (IPB) that I finished last year for Dr. Bob Eggleston (AFRL/HECS). In addition, I continue to work on that issue in this program and in our internal research and development program.*

It has been asserted that CWA can generate (or describe) human systems requirements, however, this is a point of debate. For example, in one case study, use of the CWA provided the following functional requirements for a training system (Sanderson, 2003):

- Design Objectives: training system must be designed to satisfy the training objectives of the work domain
- Data Collection: training system must be capable of collecting data related to measures of performance
- Scenario Generation: training system must be capable of generating scenarios for practicing basic training functions
- Physical Functionality: training systems must simulate the functionality of physical devices and significant environmental conditions
- Physical Attributes: training system must recreate functionally-relevant properties of physical devices and significant features of the environment

These functional requirements as generated by the CWA are not functional requirements as requirements engineers would term them so clearly there is a disconnect. *At first glance, this comment is something of a puzzle for me. What would constitute functional requirements as requirements engineers would term them? This in fact, is one of the central issues I am trying to deal with in this project and in our IRAD [Independent Research And Development] project. In addition, Vicente (1999, page 115) has provided a table that lists the types of requirements that can be derived from each of the phases of Cognitive Work Analysis. While that is a meager discussion, just one page in a 400-page book, it offers some useful ideas we can build on. I took this comment by Missy as something of a challenge and found some observations towards the* *end of this appendix that I abstracted and expanded. I offer those ideas separately in Appendix K.* It has been asserted that CWA tools can aid in the generation of "information requirements" (Miller & Vicente, 2001; Potter, Gualtieri, & Elm, 2002; Vicente, 1999), but it has yet to be established how and when information requirements can be inserted into the more comprehensive systems requirements process. Moreover, it has been shown that CWA cannot be used to generate comprehensive requirements for revolutionary intentional domain systems[16] (Cummings, 2003). In addition, as will be discussed in a subsequent section, it is not clear whether or not CWA should be used for intentional domains that are time-dependent with high degrees of uncertainty such as what occurs in command and control systems.

The real value of CWA is with intentional domains, but I am not sure that is the point being made here. The point here I think is with time dependency—practically everything we do has time dependency characteristics. I and others have explored how to deal with that in the Control Task Analysis phase although I do not believe this issue has yet been resolved effectively.

3.0 CWA and Systems Engineering

Systems engineering is not a mutually exclusive task that belongs just to "systems engineers." The systems engineering approach recognizes that to successfully build and operationally deploy a system (such as a UAV, a ship, or even a command and control network , which is really a system of systems) a principled approach must be taken such that all the different components of the system are seamlessly integrated in final design stages to meet customer requirements. The job of integrating the sub-systems does not fall just to systems engineers (who are often system analysts) and program managers, but also to any engineer of any background who will integrate his/her system with one or more additional systems.

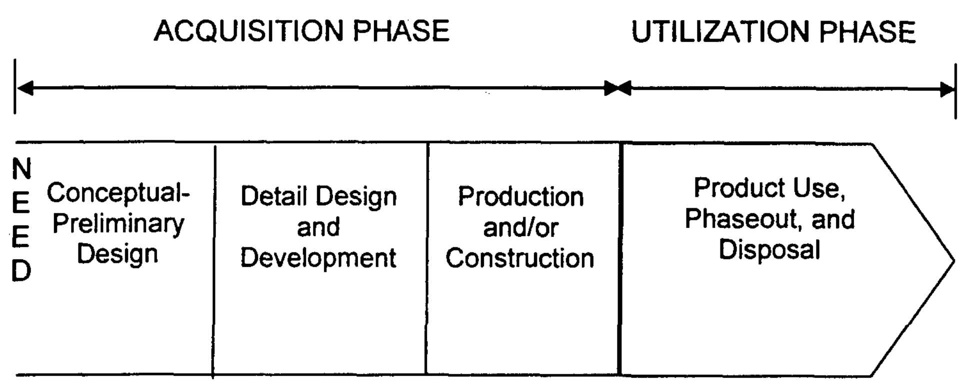

Figure J-1: The Waterfall Systems Engineering Approach

By the very nature of cognitive engineering, all cognitive engineers should be "system engineers" in that the human component is always integrated with multiple layers of the system. The primary purpose of a cognitive engineer is not to ensure the system supports the human, but

[16] An intentional domain is one in which human intentions constrain the systems such as in command and control systems, versus a "causal domain" in which physical laws of nature constrain the system.

that the human is effectively integrated into the system such that overall operational success can be achieved.

In the past, military systems acquisition typically followed a waterfall type of approach as seen in Figure J-1 (Blanchard & Fabrycky, 1998). However, recent advances in systems engineering approaches, suggest that a more concurrent approach is needed both for a leaner, more cost-effective process as well as mitigation of risk. This approach to systems engineering is known as the Spiral Model (Figure J-2, (Boehm, 1988)) and has replaced the waterfall model in most large system design and development projects.

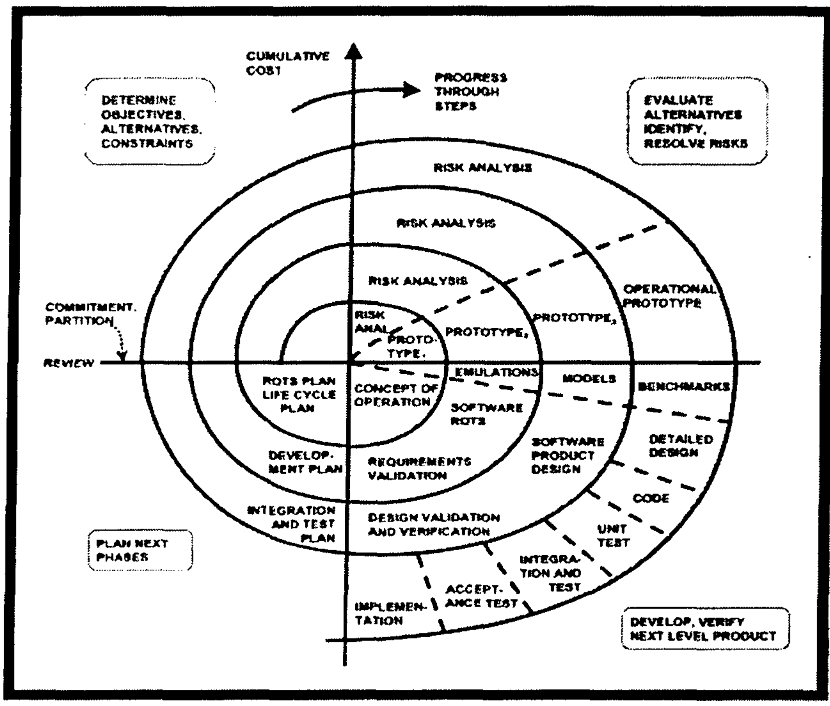

Figure J-2: The Spiral Systems Engineering Approach

While CWA takes a systems-theoretic approach in potentially determining cognitive requirements only after the larger system is mapped, *(many of us want to establish cognitive requirements before the larger system is framed—we want to influence the mapping of the larger system)* it is not a systems engineering approach, cognitive or otherwise *(so, I wonder what constitutes a systems engineering approach—my reading of systems engineering textbooks does not clarify for me how CWA fails in this regard)*. Regardless of which systems engineering model is used, in addition to the model in Figure J-2 and the need for requirements generation, key elements of systems engineering include concept exploration, demonstration and validation, system integration, cost-benefit analyses, and design and development (Smootz, 2003). CWA does not address any of these areas *(My report titled "Contribution of Cognitive Engineering to Systems Engineering" (Appendix K) reflects ideas stimulated by Missy's comments. However, I do not want to accept the position that a cognitive engineering approach needs to do all of these; for example, I believe we need to leave cost-benefit analysis to those who do this already)*. The major drawbacks to CWA are 1) no definitive link to design (and has been routinely criticized for such) *(many of us are working on this issue—and on 2 below—I believe I have made some progress on the link to design in my IPB work)*, 2) a lack of testing and verification leverage points, and other than showing vague links to other potential supra and subsystems, 3) no information is given towards effective integration strategies *(whenever I hear an engineer talk about how they integrate human capabilities with technological capabilities I am struck by how superficial and unprincipled their approach is—I accept that this is something we need to work on and it is probably something that only a cognitive engineer can do)*.

In terms of a real systems engineering model, as it stands now with its five phases, CWA is at best an analysis tool for human systems integration information requirements. *Yes, does anyone imply it should do more?* In addition to other tools such as legitimate models, computer simulations, and more traditional cognitive task analyses, CWA can aid in identification of requirements for human-system interaction. This is not a trivial statement. If CWA can be shown to reliably and clearly delineate those information requirements for what, how much, and when human interaction is needed in a system, it could revolutionize the human systems engineering process.

4.0 CWA Limitations

At the very heart of the CWA methodology is the use of the abstraction-decomposition matrix and well as abstraction hierarchies (a form of means-ends analysis). These tools in theory represent system structure at different levels of abstraction so that a system's functions can be decomposed into sub-systems. This function decomposition is not new to the field of systems engineering and in fact, under different names, has been in use much longer than CWA has been in existence. The following quote is from the most established systems engineering text in existence.

"Functional analysis is the process of translating system requirements into detailed design criteria, along with the identification of specific resources requirements at the subsystem level and below. One starts with an abstraction of the needs of the customer and works down to identify the requirements for hardware, software, people, facilities, data, or combinations thereof (Blanchard & Fabrycky, 1998)."

There are two issues here—one regarding the relationship of cognitive engineering to systems engineering and the other regarding the nature of functional analysis. I address the first issue and offer a few comments on the second in a separate appendix titled "The Relationship of Cognitive Engineering to Systems Engineering" (Appendix D).

The CWA approach to functional analysis might be clarified by consideration of the meaning of the terms ***function*** *and* ***process****. These are troubling terms in engineering and science because their range of usage is broad and they have overlapping meanings. Within Cognitive Work Analysis, Vicente (1999) has given them constrained meanings that map onto the needs of this analytic framework. A* ***function*** *is a structural property of the work domain. A* ***process*** *is a mechanism by which the behavior of the system is produced. This distinction is unusual and no other strategy of cognitive analysis makes it explicit. An underlying assumption of Cognitive Work Analysis is that the separation of structure from activity helps bring an important source of order to the analysis of complex, socio-technical systems. Even within Systems Engineering,* *where this sort of distinction would seem to offer an advantage. Functional Analysis as discussed in many texts and reports (e.g., as in Blanchard and Fabrycky, 1990) is a functional flow analysis—essentially a process analysis.*

4.1 Problems with Embedded Control Loops

However, where CWA differs from typical system engineering functional decompositions is the CWA assertion that its decompositions represent the system structure independent of any human, automation, event, or task goal. A significant drawback to this approach is that embedded control systems cannot be represented in the CWA abstraction decomposition and this causes the subsequent representation to be both artificial and likely incorrect. While current criticism of the CWA flaw has been directed towards its application to process control (Lind, 2003, 2004), this is a criticism that is even more applicable in the command and control domain. There are countless embedded control loops found at all levels of C2 such as autopilot in planes, GPS navigation, electronic intelligence, radar-tracking solutions for fire-support, etc. Military platforms and C2 networks cannot exist without embedded control loops and with network-centric warfare on the immediate horizon, the presence of embedded control loops will only increase.

I am not sure where the notion that we should embed control loops in the abstraction-decomposition map came from—I never do it and I am never tempted to do it. For me at least, this is definitely the wrong place to be thinking about control loops.

4.2 Adaptation to Revolutionary Systems

While advertised as a way to design revolutionary decision support systems, CWA can only be applied to existing systems (Cummings & Guerlain, 2003). CWA assumes an existing organizational structure, existing infrastructure, existing users, and clearly defined boundaries. For decision support systems in revolutionary systems, CWA cannot be effectively used without other cognitive task analysis methodologies such as cognitive walkthroughs and simulations.

We definitely want to assist with design of future systems, but this talk of revolutionary design has been undisciplined—any design has to come from a hybrid revolutionary-evolutionary approach. Neelam's work on team design is an excellent example of how to progress through a revolutionary-evolutionary cycle.

4.3 Problems with Intentional Domains

CWA has been shown to be effective for analyzing the human role in causal systems such as process control (Vicente, 1999), but it's usefulness in intentional domains has been questioned (Cummings, 2003; Wong, Sallis, & O'Hare, 1998). Especially critical to command and control domains, the cause-and-effect relationships due to unanticipated events cannot be traced via the structural invariants provided by CWA. In addition, as mentioned previously, CWA has serious difficulty in addressing the concept of time in systems operations. In the first phase of abstraction decomposition, the analyst spends a great deal of time mapping out what, how, and why relationships. While this may be effective for causal systems whose operations do not change dramatically over time, this is a limitation of CWA that makes its application to command and control (intentional) systems extremely limited, as is the inability of CWA to incorporate cause-and-effect tracings for unanticipated events in intentional domains. Any functional or design requirement that comes from a CWA analysis for a command and control system should be suspect since there is no principled way within the analysis to address the critical time constraints.

Cause-effect and time criticality are two different issues and they are mixed up here—I have addressed time constraints above. Regarding cause-effect, it is not entirely clear to me that we should be mapping out cause-effect in cognitive engineering—although I may be unclear about what is meant here by that. Peter Kugler offered some thoughts on prediction for intentional systems in his commentary in Appendix I—those comments are relevant to this issue of cause-effect.

4.4 Ill-defined Phases of Analysis

CWA is a laborious process and the last three of its five phases are very vaguely defined. Indeed, many researchers and analysts will only complete the first two phases and call their results a CWA. Specifically the analysis of strategies, social, organizational, and cooperation analysis, and worker competencies phases do not have similar principled tools that are used in the domain and control task analysis phases. Despite numerous tools that could be applied to these areas (social network theory, social judgment theory, decision trees, macrocognition, human performance modeling, etc.), it is not clear how and if these phases can provide any real contribution to the analysis of a system and the generation of any meaningful requirements for decision support.

These phases in CWA are essential, but I agree we have not yet done a good job on them. I suspect that the fact that we have not done a good job on the later phases leads others to express concern about including properties in the work domain analysis that should be dealt with in the later phases.

5.0 Structure vs. Process

In the proposal[17] there is a desire to separate structure and process. For causal systems this may be possible but for C2 systems which are inherently process driven this may not be possible. In the proposal, structure is defined as the instantiation of physical resources in a workspace. In C2 the overarching purpose of the system is to move the structure as the environment dictates. C2 is fundamentally a process and this may be yet another reason why CWA is not applicable to C2. Even Rasmussen warns that functional decomposition according to structural elements cannot occur because of human adaptation (Rasmussen et al., 1994).

No, structure is not just physical resources—it also involves functions and constraints—nothing we do is fundamentally process—there is always some form of supporting structure and the claim in the proposal is that it is useful to map that out as distinct from process. I further want to argue that we need to focus on designing structure. Many people want to design process, and while I do think we can have some influence there, the design of process by those who are not

[17] The document that Dr. Cummings critiqued, "Forms of Representation for Cognitive Demands in System Acquisition" was actually the proposal that Dr. Lintern submitted to AFRL/HECS for this effort. It is sometimes referred to as the "proposal" in this appendix.

subject matter experts carries enormous risk. One of the major claims out of cognitive work analysis is that we need to have operators "complete the design." This means, we build the structure and they decide how to use it to accomplish the purposes for which the system was built. We can help and guide the design of process but we need to be very careful that we do not impose clumsy and brittle processes on those who must use the system. I have argued elsewhere that this imposition of clumsy and brittle processes on workers is the dominant cause of accidents in high-risk systems.

Perhaps the distinction should be made between structure of decision support interfaces as opposed to physical resources. For example, how an interface is laid out can be structure and the processes are the functionalities supported such as communications, health and status monitoring, introducing new targets etc. In this case structure should be guided by basic cognitive and usability principles in conjunction with an understanding of process outcomes and goals. Unfortunately at this low level, CWA is not as useful as cognitive tasks analysis tools.

6.0 Conclusions

CWA as it stands now seems to be an effective tool for designers who need to develop abstract representation or maps of a complex system. One potential CWA application that is not addressed explicitly is that indeed the main strength of CWA may be to help designers elicit knowledge from subject matter experts. This is not a trivial benefit. It is often very difficult for cognitive engineers to grasp all the nuances of human interaction in complex systems so if the CWA methodology aids the practitioner in both identifying critical relationships and mapping them in relation to other systems, then this is a valuable tool. However, caution must be taken in that such linear two-dimensional representations can cause researchers to miss critical relationships (a hammer looking for a nail).

While CWA has merit in some areas, this report has identified four major problem areas in the application of the CWA methodology to command and control systems: 1) embedded system representation, 2) application to intentional domains, 3) adaptation to revolutionary systems, and 4) ill-defined phases of analysis. In addition, the disconnect between CWA and systems engineering was discussed and is particularly problematic in translating any information requirements to established functional and design requirements, within the larger systems engineering process.

The following recommendations highlight specific areas of potential exploration:

- Formalizing a human systems integration requirements generation tool that could include CWA or elements thereof.
- Significantly more research is needed in better defining the last three phases of CWA and demonstrating how they add overall value to the requirements process.
- Development of a more principled application of CWA as a knowledge elicitation and representation tool.
- Formalize a methodology in which CWA can be shown to provide consistent information requirements that can translate to display design.

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APPENDIX K. CONTRIBUTION OF COGNITIVE ENGINEERING TO SYSTEMS ENGINEERING

BACKGROUND

In this appendix, Dr. Lintern discusses ideas stimulated by his reading of the report from Dr. Missy Cummings (see Appendix J). Dr. Cummings' ideas are restated in italics in the discussion below.

Dr. Lintern serves Chief Scientist at General Dynamics - Advanced Information Engineering Services. Dr. Lintern is a Subject Matter Expert in the field of Cognitive Systems Engineering. He previously served as Director of Human Factors for the Air Operations division of Australia's Defense Science and Technology systems research where he managed and built a program in Cognitive Systems Engineering.

DISCUSSION

CWA is a systems-theoretic approach, not a systems engineering approach (a point John Flach keeps repeating, we possibly have not been sufficiently explicit about this in general).

Systems Engineering focuses on *requirements generation*. We need to support that focus but we do not currently do a good job of requirements generation. We need to work on that.

Important Challenges, in addition to requirements generation, how can Cognitive Engineering help with:

- *Concept Exploration* (primarily the Abstraction-Decomposition (A-D) matrix)
- *Demonstration* (probably not)
- *Validation* (validation of what?)
- *System Integration* (yes, with Human-System Integration)
- *Cost-Benefit Analyses* (marginal contribution)
- *Design and Development* (yes, with the Human-System Integration elements of Design and Development)

Need to work on:

- *Definitive link to design* (we are working this issue and have made progress)
- *Testing and verification leverage points* (we can contribute to this)
- *Effective integration strategies* (we can develop these)

Other tools such as models, computer simulations, and more traditional cognitive task analyses can aid in identification of requirements for human-system integration. (yes, no doubt about this—and in testing design options)

If CWA can be shown to reliably and clearly delineate those information requirements for what, how much, and when human interaction is needed in a system, it could revolutionize the human systems engineering process, e.g.,

- By laying out functional requirements in the Abstraction-Decomposition matrix and then identifying what needs to be accomplished within the system, Cognitive Work Analysis takes the first step towards identifying staffing requirements, i.e., one or more agents need to be allocated to each module of work—although, at this stage, there is no resolution of whether they should be machine agents or human agents.

- Control Task Analysis and Strategies Analysis will identify the ways in which things can be accomplished—however, to fully resolve the machine-agent versus human-agent allocations, it is necessary to integrate the results of these analyses with insights from studies of interactions between humans and automation.

The primary purpose of a cognitive engineer is not to ensure the system supports the human, but that the human is effectively integrated into the system such that overall operational success can be achieved.

I have a mixed response to this comment—I agree that the system is not designed to support the human participants and so in that sense it is misleading to say that our goal is *to ensure the system supports the human*, but my specific problem with the second part of this statement—*ensure that the human is effectively integrated into the system*—is that it accords priority to the system so that humans might be thought of as supporting the system. The priority is to satisfy the (human-related) purposes for which the system is designed; the purposes that constitute *operational success.*

This is similar to the problem I have with Morten Lind (Appendix G) when he argues that human operators need to understand the system. While I agree with this claim, the statement on its own ignores the prior requirement to design a system so that it is compatible with the robust cognitive style of experienced operators, thus enabling the understanding of the system by the operators.

I typically refer to requirements for Human-System Integration, which seems to carry the right message. The focus of cognitive engineering is restricted to the relationship between human participants and the system technology, and we need to ensure that the technology is compatible at that seam with a robust human cognitive style.

As cognitive engineers, we need to confine our requirements specifications to human-system integration issues, but as shown by the table below from Vicente (1999)[18] there is at least some thinking in this area. I accept that it is a neglected area but it is one in which at least some of us are making progress.

RELATIONSHIPS BETWEEN THE FIVE PHASES OF CWA AND VARIOUS CLASSES OF SYSTEMS DESIGN INTERVENTIONS. (TABLE 5.1 from page 115, Vicente 1999)

1. Work Domain

What information should be measured? (sensors)

What information should be derived? (models)

How should information be organized? (database)

[18] Vicente, K. (1999). *Cognitive Work Analysis. Toward safe, productive, and healthy computer-based work.* Mahwah, NJ: Erlbaum.

2. Control Tasks

What goals must be pursued and what are the constraints on those goals? (procedures or automation)

What information and relations are relevant for particular classes of situations? (context sensitive interface)

3. Strategies

What frames of reference are useful? (dialog modes)

What control mechanisms are useful? (process flow)

4. Social-Organizational

What are the responsibilities of all of the actors? (role allocation)

How should actors communicate with each other? (organizational structure)

5. Worker Competencies

What knowledge, rules, and skills do workers need to have? (selection, training, and interface form)

SUMMARY

For me, the most valuable part of Missy's report was the commentary on the nature of systems engineering. The primary concern with requirements generation, and then subsequently with Concept Exploration, Demonstration, Validation, System Integration and Cost-Benefit Analyses forced me to ponder first, whether we are doing a good job on any of these dimensions and second, how we might develop our capability on the dimensions to which we should be able to contribute. I take this as a reasonable statement of an agenda for this project and for any effort in which we are trying to integrate cognitive engineering with systems engineering.